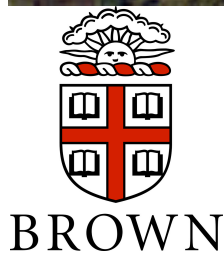
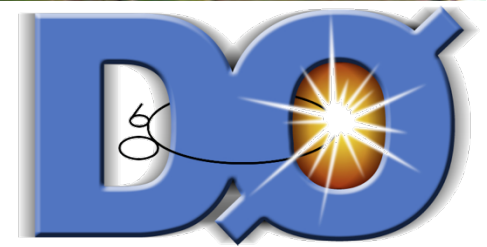




Top Physics and Lessons for the LHC



Meenakshi Narain
Brown University



LHC@BNL workshop June 19, 2009

top at Fermilab

- 14 years ago...
...we observed a few handfuls of top quarks.

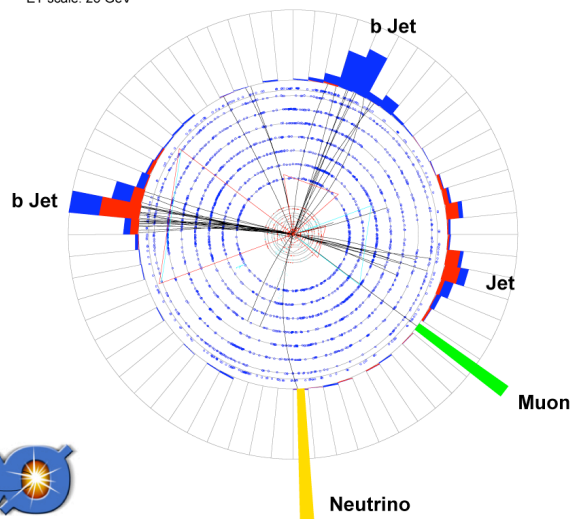
- Recently...

Observed EWK production process: single top quark

DØ Experiment Event Display
Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis

Run 223473 Evt 27278544 Sun Jul 23 19:21:41 2006

ET scale: 28 GeV

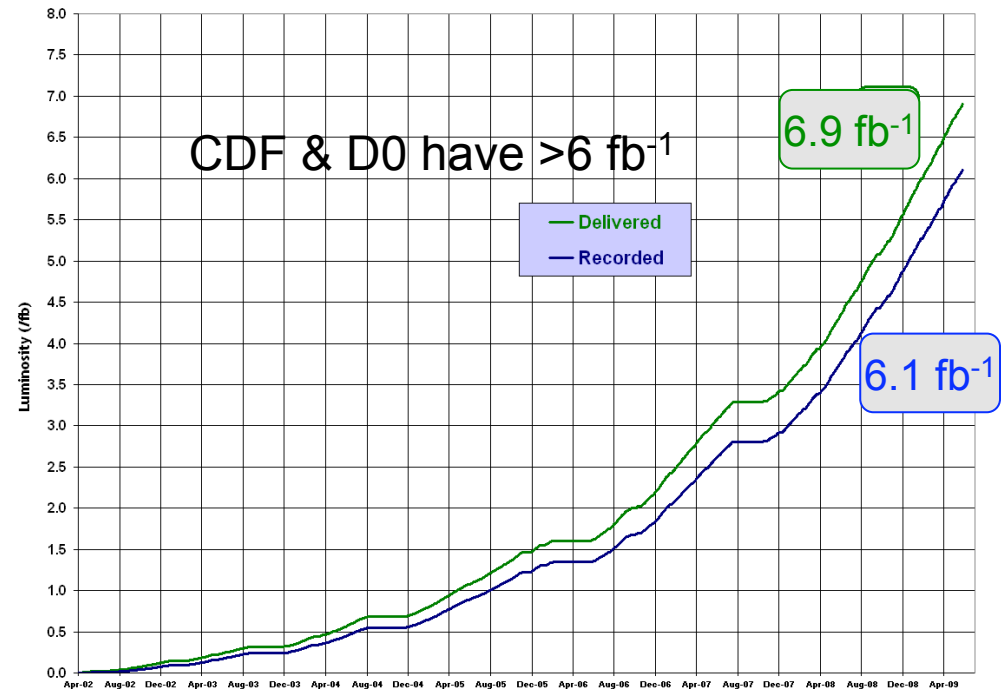


- today...



Run II Integrated Luminosity

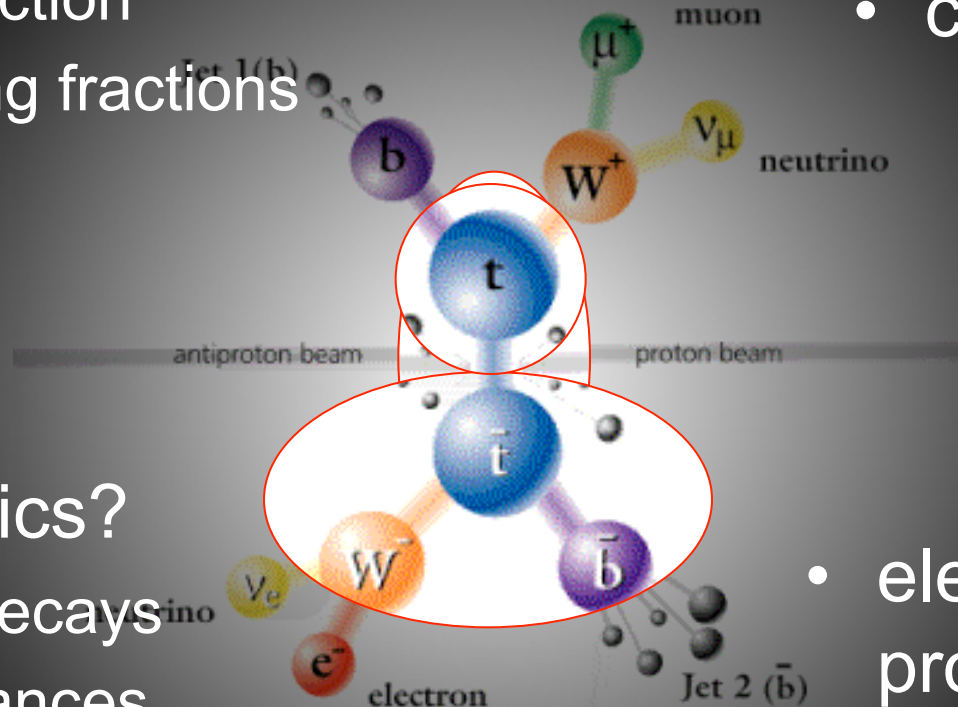
19 April 2002 - 14 June 2009



...we are performing detailed studies of 1000s of top decays

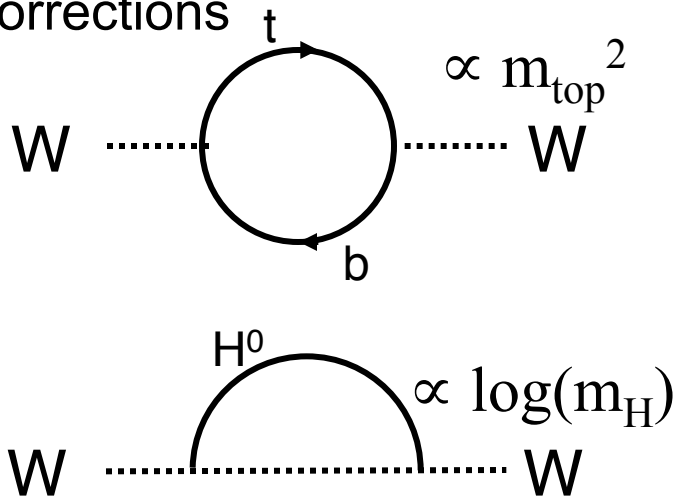
outline

- strong production
 - cross section
 - branching fractions
- mass
- couplings
- new physics?
 - FCNC decays
 - $t\bar{t}$ resonances
 - $t\bar{b}$ resonances
 - H^+
 -
- electroweak production
 - $|V_{tb}|$

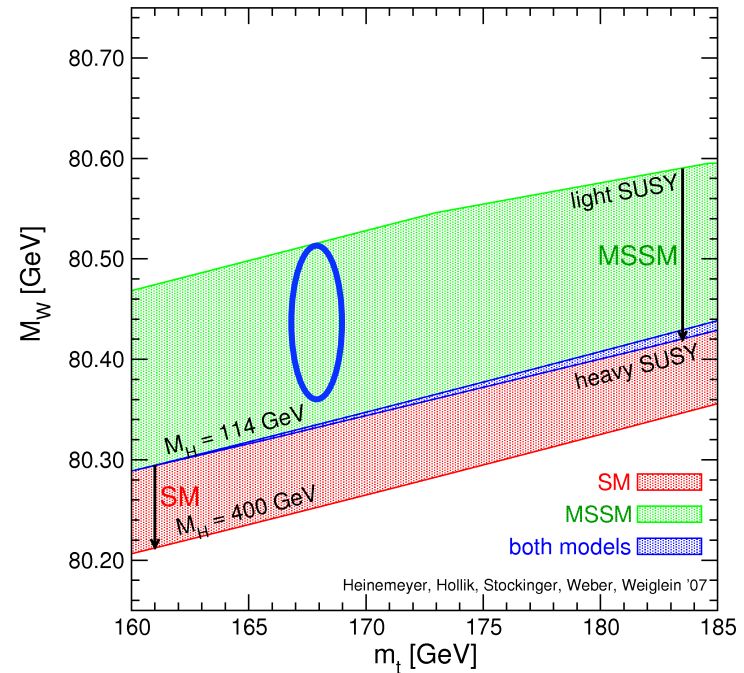


why is the top quark important?

- most massive elementary particle
 - dominant contributor to radiative corrections

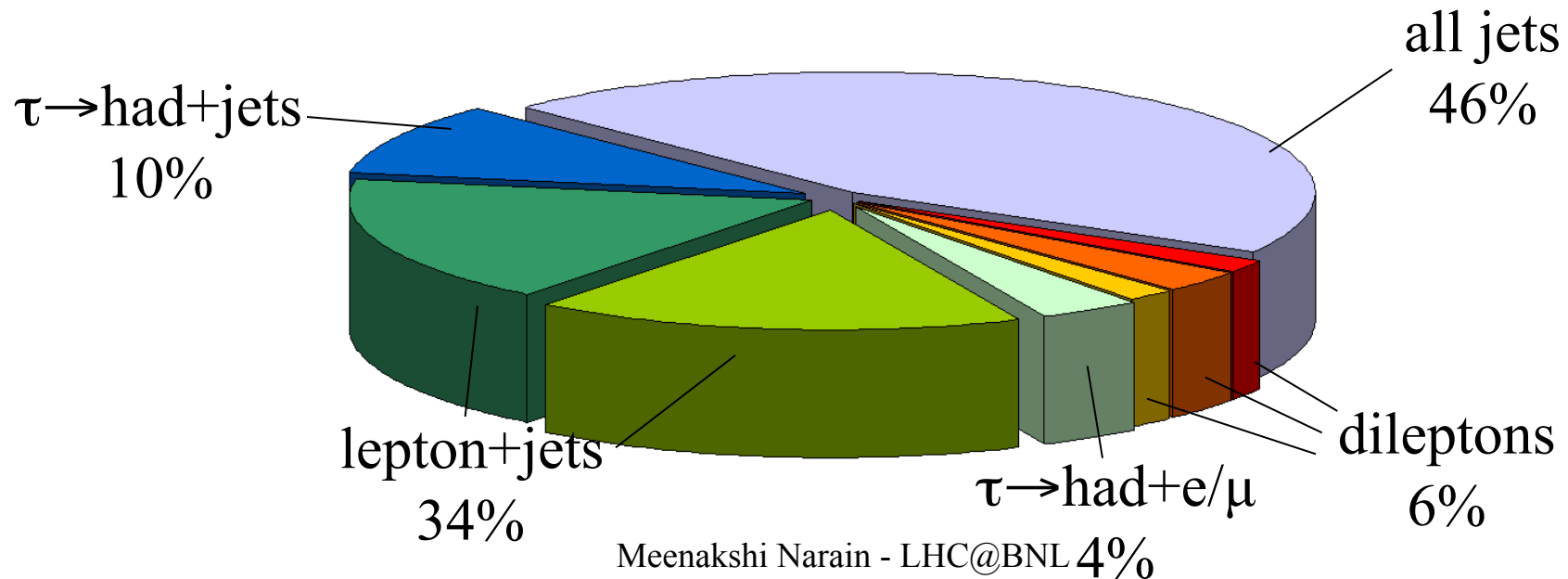
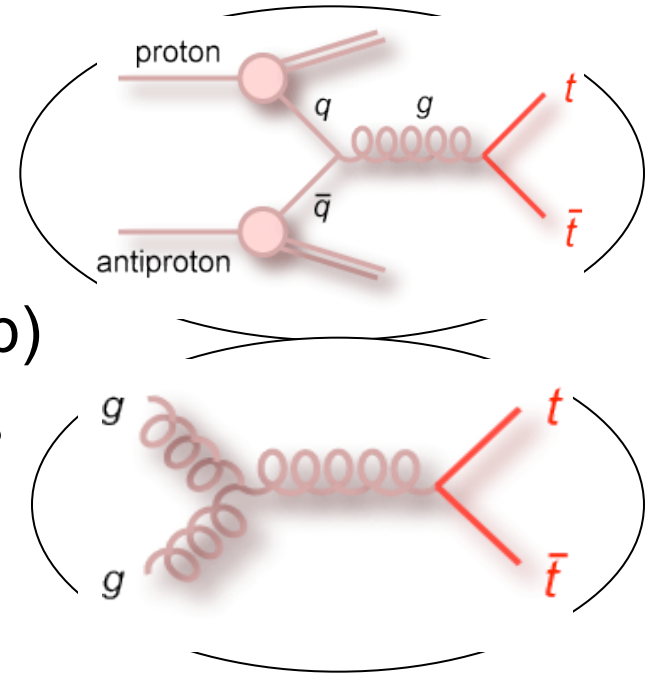


- how is its mass generated?
 - topcolor?
- does it couple to new physics?
 - massive G, heavy Z', H⁺, ...



top-antitop production

- strong interaction
 - top-antitop pairs ($\sigma = 7.6 \pm 0.6$ pb)
- final state signatures for top-antitop pairs
- $t \rightarrow Wb$ with $B \approx 100\%$
 - tagging b-jets important
 - $W \rightarrow qq$ with $B \approx 67\%$; $W \rightarrow \ell\nu$ with $B \approx 11\%$
 - $\tau \rightarrow e\nu\nu/\mu\nu\nu$ with $B \approx 17\%$



Tevatron phases

- Run Ia (20 pb^{-1} - handful of events)
 - e-mu is the golden channel to find top
 - if top is really massive will we be able to see it?
- Run Ib (160 pb^{-1} <100 events)
 - top quark is really massive
 - need to use the hadronic signatures
 - l+jets is the golden channel
 - measure cross section and mass
- Run IIa (1 fb^{-1} 100s of events)
 - advanced analysis methods
 - more properties measured
 - precision measurements
 - combination of all measurements of an observable
- Run IIb ($8? \text{ fb}^{-1}$ 1000s events)
 - beginning to get systematically limited
 - consistency of measurements of different observables
 - look at the whole picture

Lessons learned

- Be prepared to abandon your premise
 - To find the top quark it was necessary to re-optimize the search for much higher mass using different channels and features in the event than initially imagined.
 - To optimize sensitivity and resolution it was necessary to invent new analysis techniques.
 - b-tagging
 - Mass measurement in dilepton channel
 - Matrix element/event-by-event likelihood techniques
 - In situ calibration of jets with $W \rightarrow qq$
 - Neural networks, decision trees, etc.

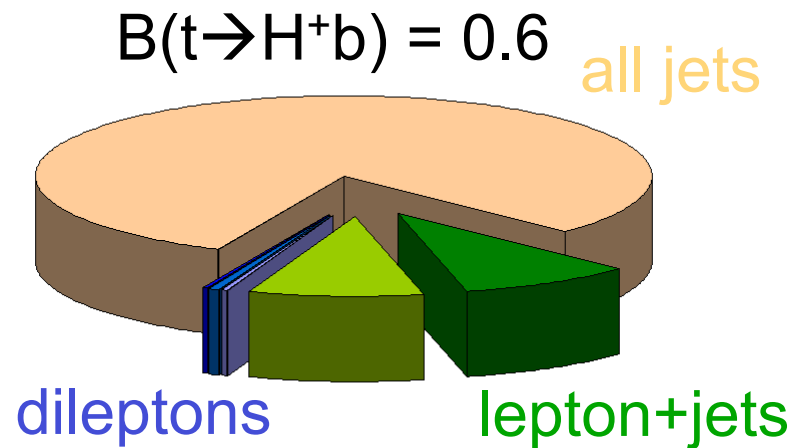
Lessons learned

- Develop a simulation that mimics detector performance
 - Crucial to extrapolate from e.g. background to signal regions
 - Study systematic effects
 - Realize what you cannot simulate well (jet multiplicity, fake rates)
 - Often limited by rate at which events could be simulated
 - need for fast MC simulation tuned to data
- Control samples to verify distributions, estimate backgrounds, efficiencies for triggers, lepton-id etc.

Selected Results from Dzero

why measure the $t\bar{t}$ cross section?

- cross section analysis
 - basic understanding of signal and background necessary for further study
 - consistency between channels
 - decay branching fractions
 - are there non-standard decays?

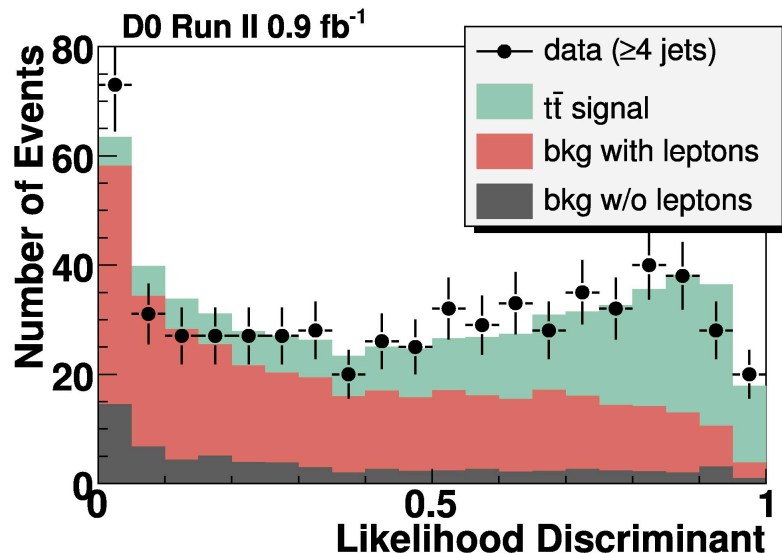


$t\bar{t}$ cross section in $l+jets$ channel

- extract top fraction using event topology
 - angles, momentum sums, and event shape variables
 - dominated by statistical uncertainties
- count number of events with at least one b-tagged jet
 - smaller statistical uncertainty
 - large systematic uncertainty from jet energy calibration and b-tagging

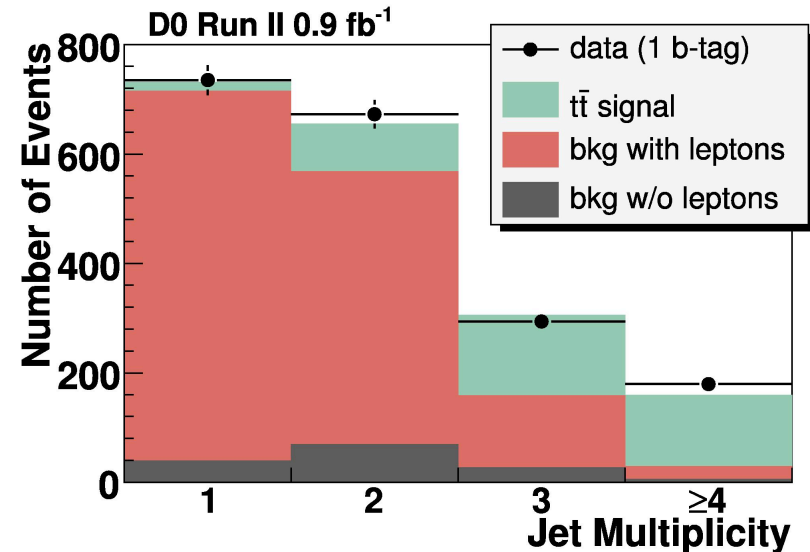
D0 (0.9 fb^{-1})

$\sigma = 6.6 \pm 0.8(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{lum}) \text{ pb}$



D0 (0.9 fb^{-1})

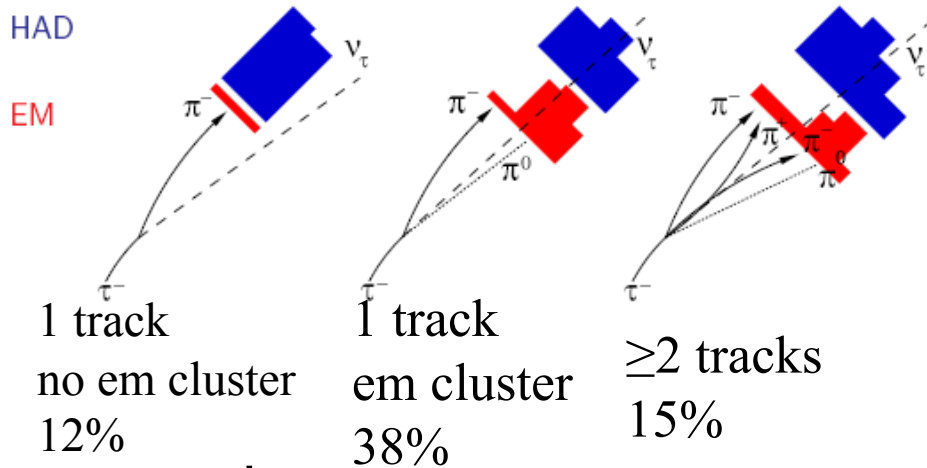
$\sigma = 8.1 \pm 0.5(\text{stat}) \pm 0.7(\text{syst}) \pm 0.5(\text{lum}) \text{ pb}$



ttbar cross section in τ channels



- interesting because of
 $t \rightarrow H^+ b$, $H^+ \rightarrow \tau \nu$
- 3 types of hadronic τ decays

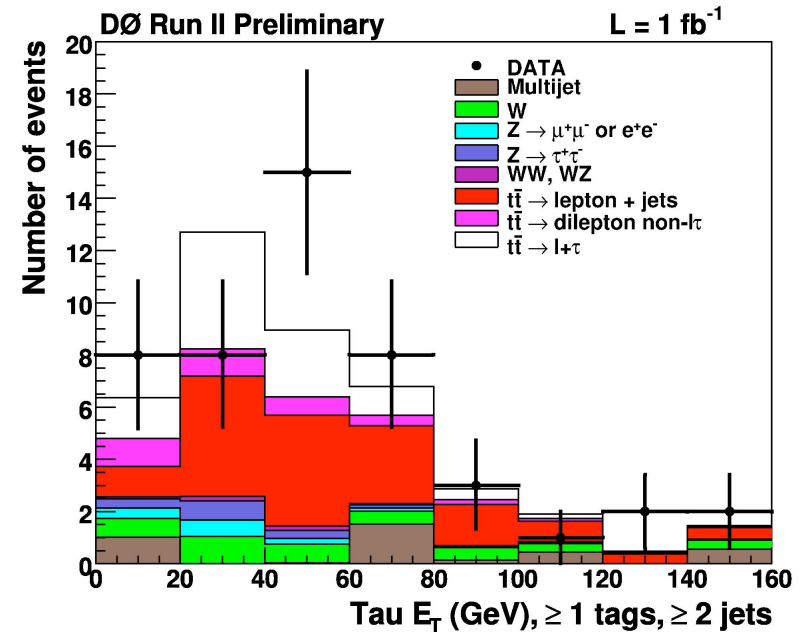


- require
 - 1 τ , 1 e/μ , ≥ 2 jets, missing p_T
 - 1 jet is b-tagged

$$\sigma = 7.32^{+1.3}_{-1.2}(\text{stat})^{+1.2}_{-1.1}(\text{syst}) \pm 0.4(\text{lum}) \text{ pb } (2.2 \text{ fb}^{-1})$$

$$\sigma B(\text{tt} \rightarrow l\tau) = 0.19 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}) \pm 0.01(\text{lum}) \text{ pb } (1 \text{ fb}^{-1})$$

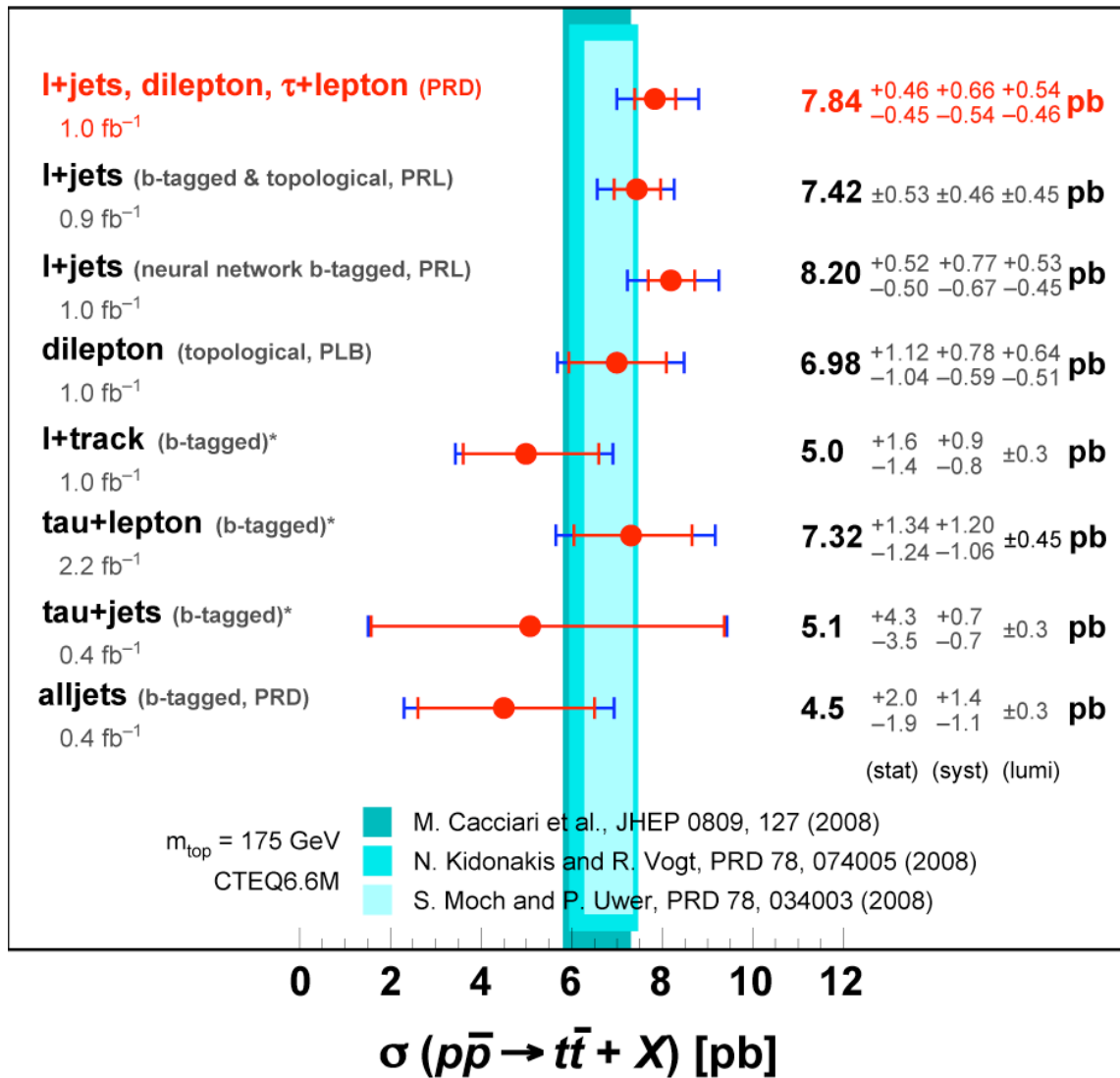
- neural networks distinguish τ decays from background



ttbar cross section summary

DØ Run II * = preliminary

May 2009



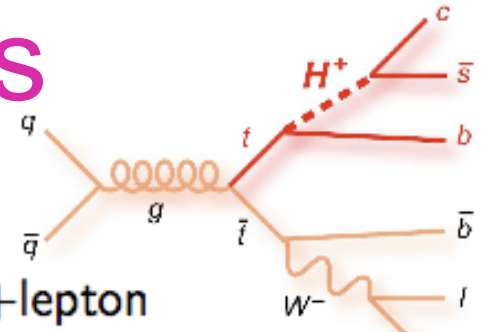
Source	$\Delta\sigma_{t\bar{t}}$ (pb)	
Statistical only	+0.47	-0.46
Lepton identification	+0.15	-0.14
Tau identification	+0.02	-0.02
Jet identification	+0.11	-0.11
Jet corrections	+0.19	-0.16
Tau energy scale	+0.02	-0.02
Trigger modeling	+0.11	-0.07
b jet identification	+0.34	-0.32
Signal modeling	+0.17	-0.15
Background estimation	+0.14	-0.14
Multijet background	+0.12	-0.12
Luminosity	+0.56	-0.48
Other	+0.15	-0.14
Total systematic uncertainty	+0.78	-0.69

non standard decay modes

- New particles in final state may alter $\sigma(t\bar{t})$:

$$\sigma_{t\bar{t}}^{\text{Ch}} = \sigma_{t\bar{t}} \cdot \frac{B^{\text{BSM}}(t\bar{t} \rightarrow \text{Ch})}{B^{\text{SM}}(t\bar{t} \rightarrow \text{Ch})}$$

Ch = ℓ + jets, Dilepton, τ + lepton



- Check cross section ratios

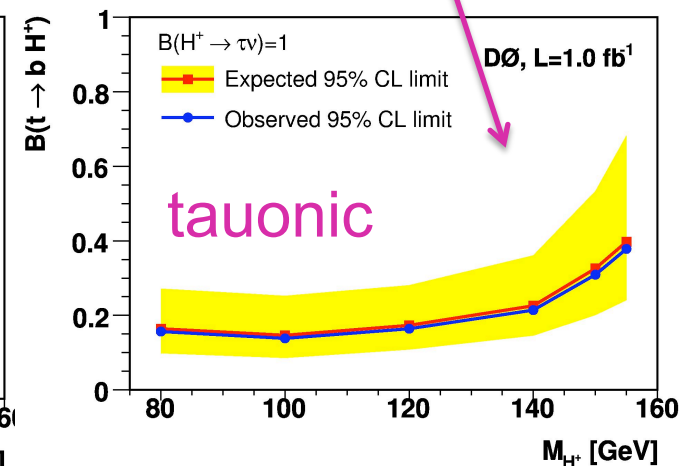
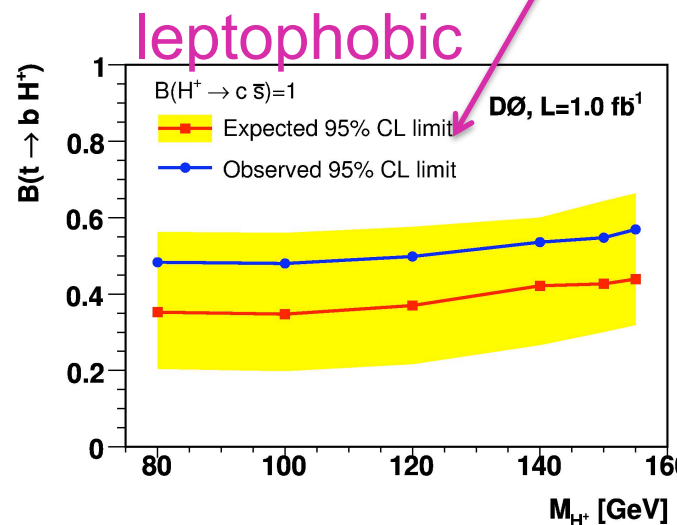
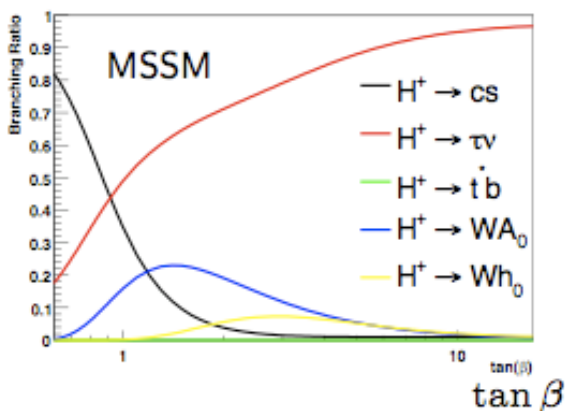
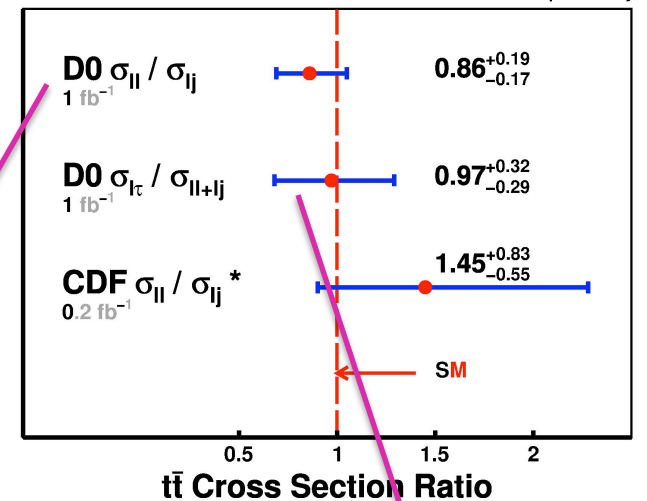
$$\sigma_{t\bar{t}}^{\ell+\text{jets}} / \sigma_{t\bar{t}}^{\text{Dilepton}} / \sigma_{t\bar{t}}^{\tau+\ell}$$

- Many systematic uncertainties are canceled in the ratios

- Within MSSM depending on $\tan\beta$

$H^\pm \rightarrow cs$ or $\tau\nu$ may dominate.

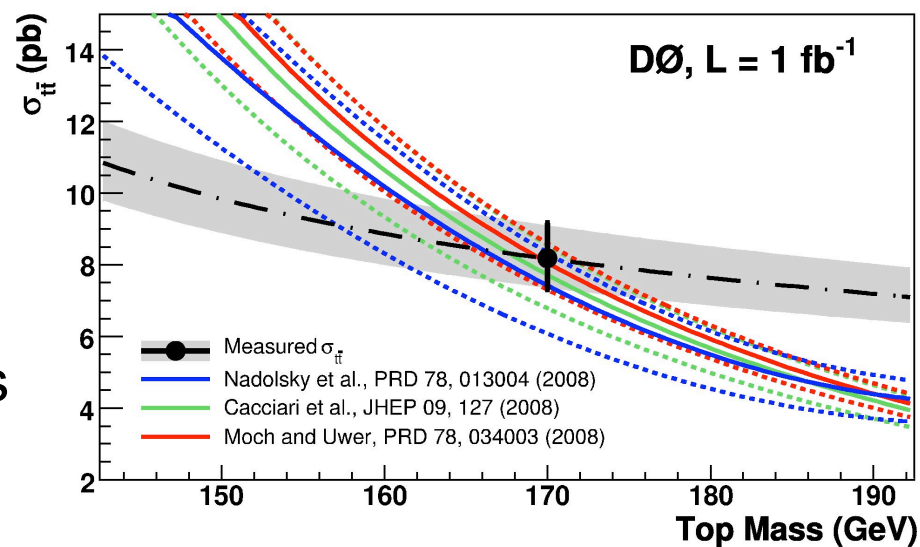
Tevatron



implications of cross section



- compare with theory to obtain mass measurement
 - Less sensitive to the non-perturbative QCD effects
- Construct likelihood with measurements and define theory likelihoods according to PDF and scale uncertainties as in refs 1-4.
- Determine joint theory and expt'al likelihood, integrate over the cross section & get 68% CL.

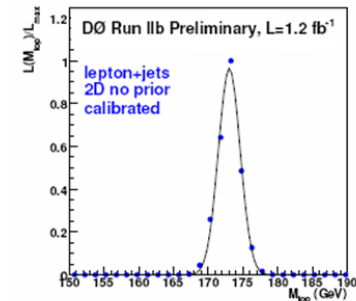
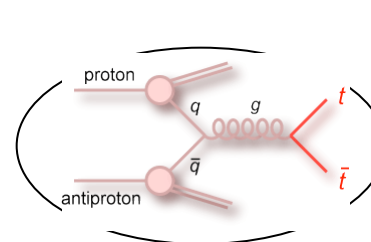
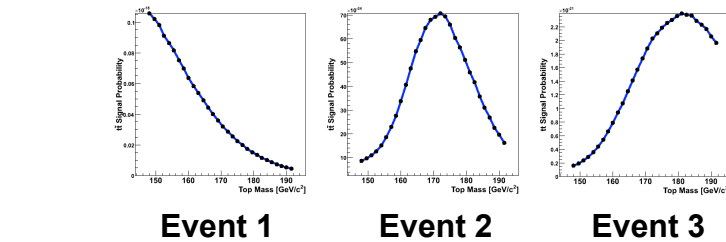
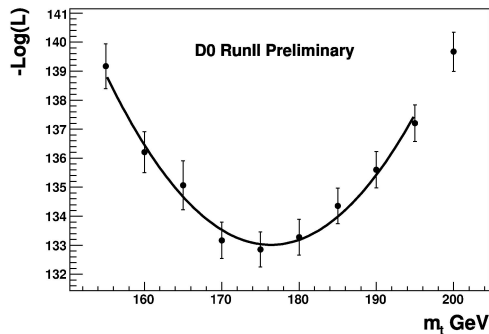
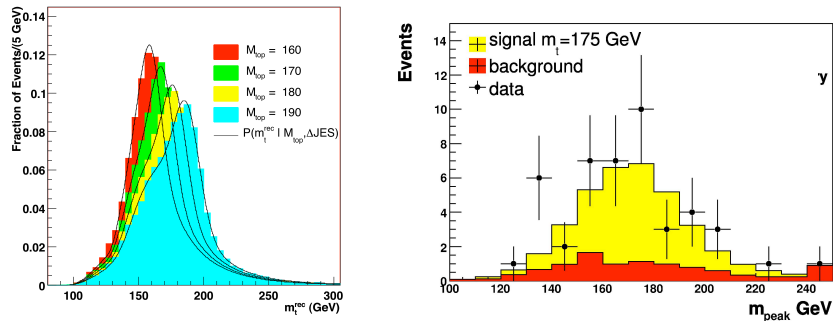


1. Nadolsky et. al., Phys. Rev. D 78 013004 (2008); W. Beenakker et. al. , Phys. Rev. D 40, 54 (1989).
2. Cacciari et al., JHEP 09, 127 (2008).
3. Moch & Uwer, Phys. Rev. D 78 034003 (2008).
4. Kidonakis & Vogt, Phys. Rev. D 78 074005 (2008).

Theoretical computation	m_t (GeV)
NLO [1]	$165.5^{+6.1}_{-5.9}$
NLO+NLL [2]	$167.5^{+5.8}_{-5.6}$
approximate NNLO [3]	$169.1^{+5.9}_{-5.2}$
approximate NNLO [4]	$168.2^{+5.9}_{-5.4}$

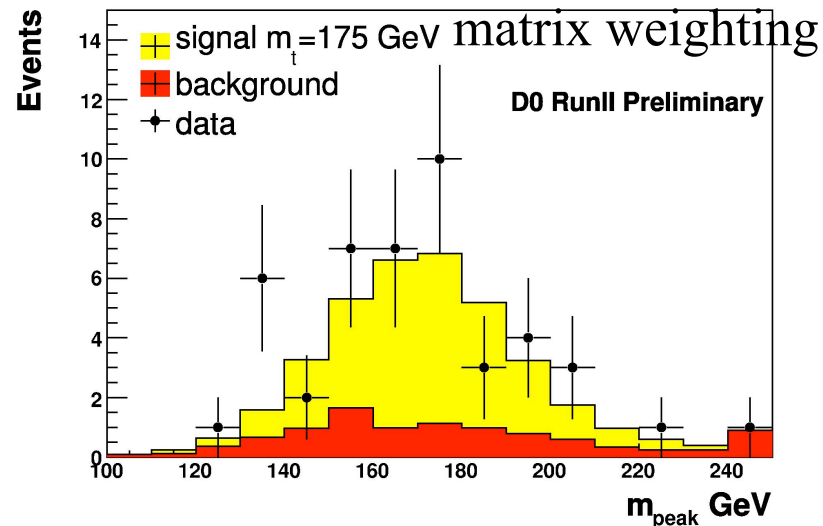
top mass measurement

- template fits
 - mass estimator (eg best m_t from kinematic fitter)
 - fit probability density functions from simulated $t\bar{t}$ events and background to data
- event-by-event likelihood
 - for each event determine likelihood as a function of m_t (eg by integrating over LO matrix element)
 - extract mass from peak of joint likelihood



dilepton channel

- D0 (1 fb^{-1})
- matrix weighting and neutrino weighting techniques
- compute weight curve as a function of top mass for each event
- template fit to mass distribution
- Combined measurement:

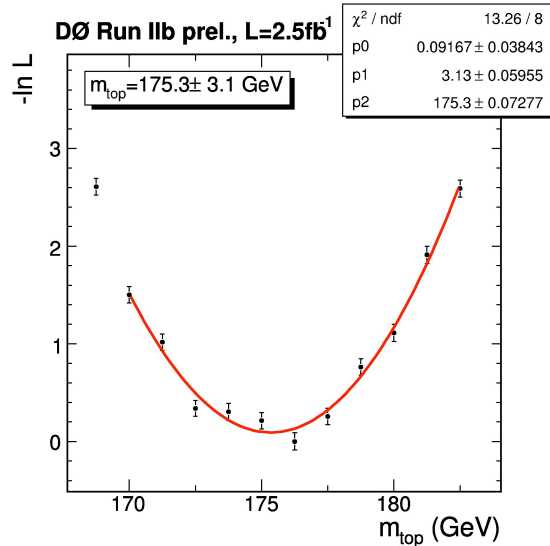


$174.7 \pm 4.4(\text{stat}) \pm 2.0(\text{syst}) \text{ GeV}$

Source of uncertainty	νWT_h [GeV]	MWT [GeV]
<i>b</i> fragmentation	0.4	0.4
Underlying events modeling	0.3	0.5
Extra jets modeling	0.1	0.3
Event generator	0.6	0.5
PDF variation	0.2	0.5
Background template shape	0.4	0.3
Jet energy scale	1.6	1.2
<i>b</i> /light response ratio	0.3	0.6
Sample dependent JES	0.4	0.1
Jet resolution	0.1	0.2
Muon/track resolution	0.1	0.2
Electron resolution	0.1	0.2
Jet identification	0.4	0.5
MC corrections	0.2	0.2
Background yield	0.0	0.1
Signal shape modeling	0.8	0.8
MC calibration	0.1	0.1
Total systematic uncertainty	2.1	2.0

dilepton channel

- D0 (3.6 fb^{-1})
 - compute event weight using LO matrix element
 - Use electron-muon events
 - Clean sample, little background



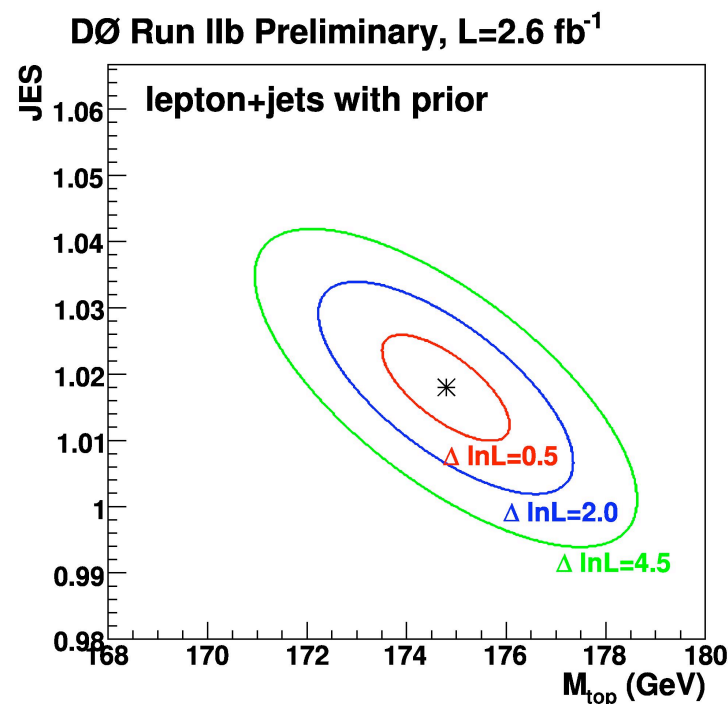
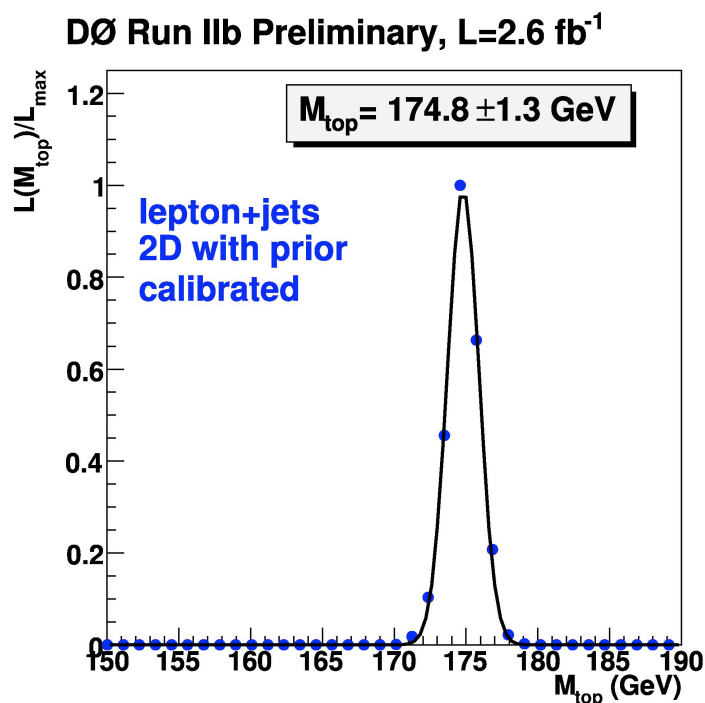
Uncertainty	$e\mu$ Run IIb [GeV]
JES up	-1.5
JES down	+1.8
b quark JES	+1.4
jet resolution up	-0.7
jet resolution down	+0.7
jssr shifting	+0.1
muon smearing up	-0.0
muon smearing down	+0.3
b quark fragmentation	± 0.3
PDF uncertainty up	-0.2
PDF uncertainty down	+0.1
fit uncertainty	± 0.4
signal modeling	± 0.4
background fraction up	-0.1
background fraction down	+0.2
TOTAL	$+2.5$ -1.8

$174.7 \pm 2.9(\text{stat}) \pm 2.4(\text{syst}) \text{ GeV}$

lepton+jets

best precision

- matrix element analysis (3.6 fb^{-1})
 - integrate over LO matrix element to get likelihood for event as a function of top quark mass
 - in situ jet energy calibration using $W \rightarrow qq$ decay
 - peak of joint likelihood = top quark mass



D0: $173.7 \pm 0.8(\text{stat}) \pm 1.6(\text{syst} \oplus \text{jcs}) \text{ GeV}$

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Lepton+jets systematics:

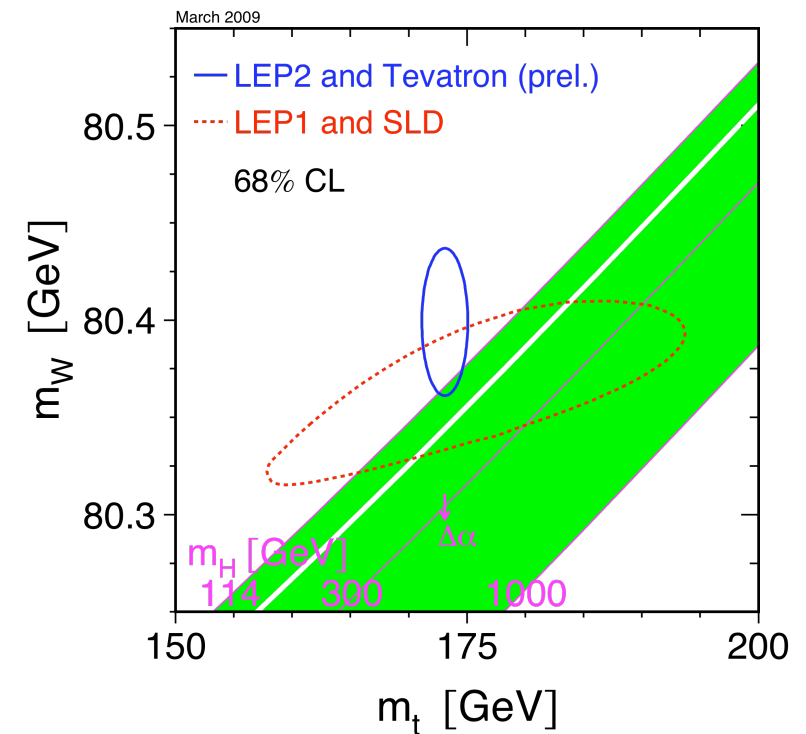
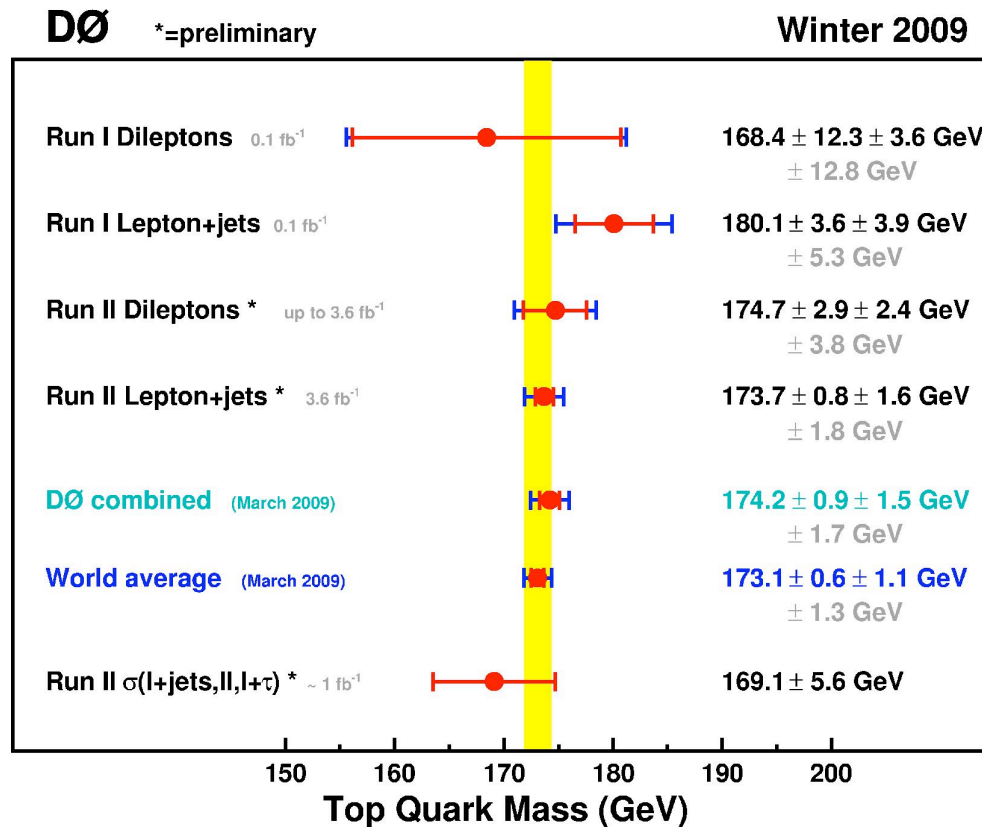
- D0

Source	Uncertainty (GeV)
Higher Order Effects	± 0.25
ISR/FSR	± 0.26
Hadronization and UE	± 0.58
Color Reconnection	± 0.50
PDF uncertainty	± 0.24
Residual JES uncertainty	± 0.21
Relative b /light response	± 0.81
Sample-dependent JES	± 0.56
Jet ID efficiency	± 0.26
Jet energy resolution	± 0.32
Plus a few smaller sys <0.2	
Total	± 1.44

Combination (as of winter '09)

D0 winter '09

$$m_{\text{top}} = 174.2 \pm 0.9(\text{stat}) \pm 1.5(\text{syst}) \text{ GeV}$$



$$\delta m/m < 1\%$$

Run II goal: $\delta m \approx 1 \text{ GeV}$

<http://tevewwg.fnal.gov/top/>

<http://lepewwg.web.cern.ch/LEPEWWG/plots/winter2009/>

theory issues

- what mass are we measuring?
 - Pole mass? (direct msm't calibrate to MC).
 - understanding required for consistency checks and M_H prediction
 - EW precision fits use \overline{MS} mass
- are we missing any important effects?
 - Color reconnection
- for the LHC, the complementary approach from measurements using cross section may have the potential to eventually get to similar level of systematic uncertainties?

analysis trends

- multivariate analysis methods
 - needed to get optimal sensitivity
 - require good understanding of detector and simulation

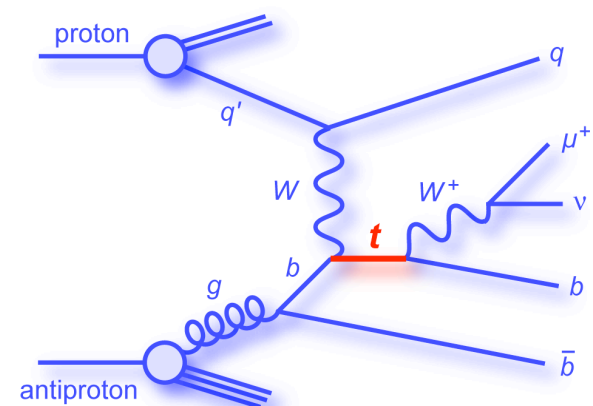
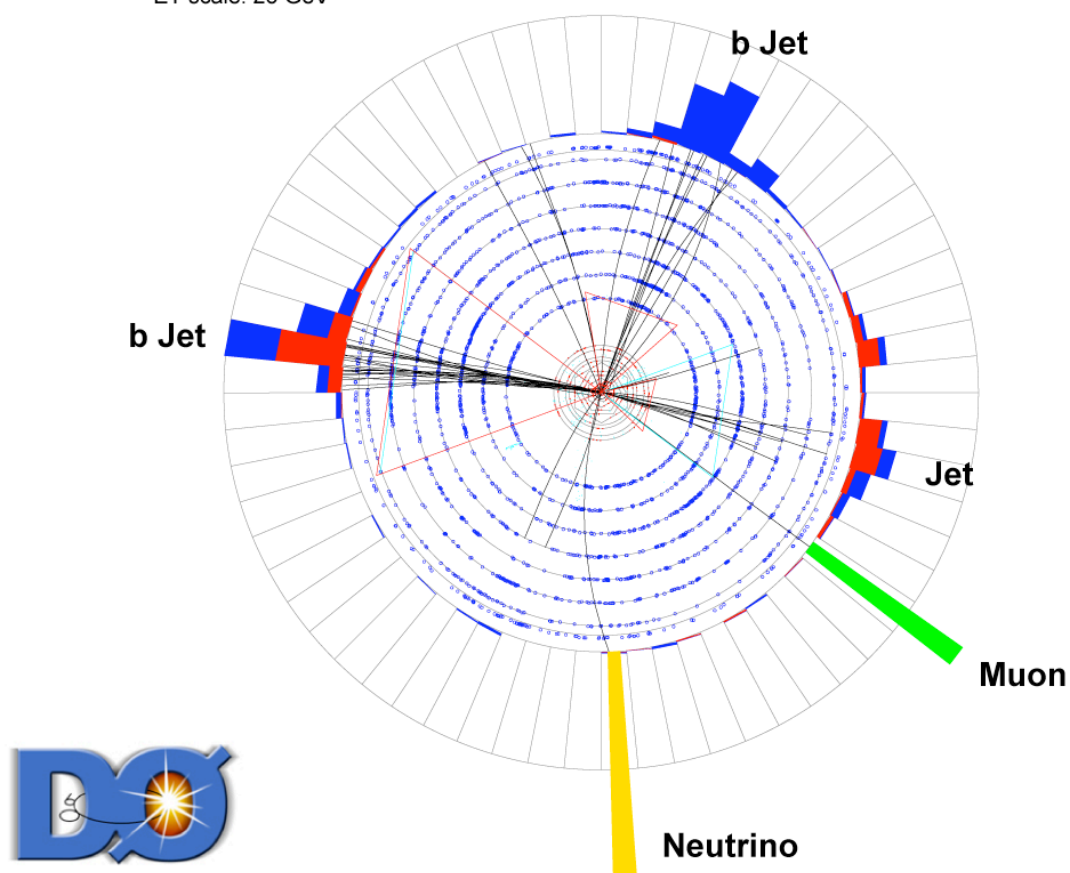
observation of single top production

DØ Experiment Event Display

Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis

Run 223473 Evt 27278544 Sun Jul 23 19:21:41 2006

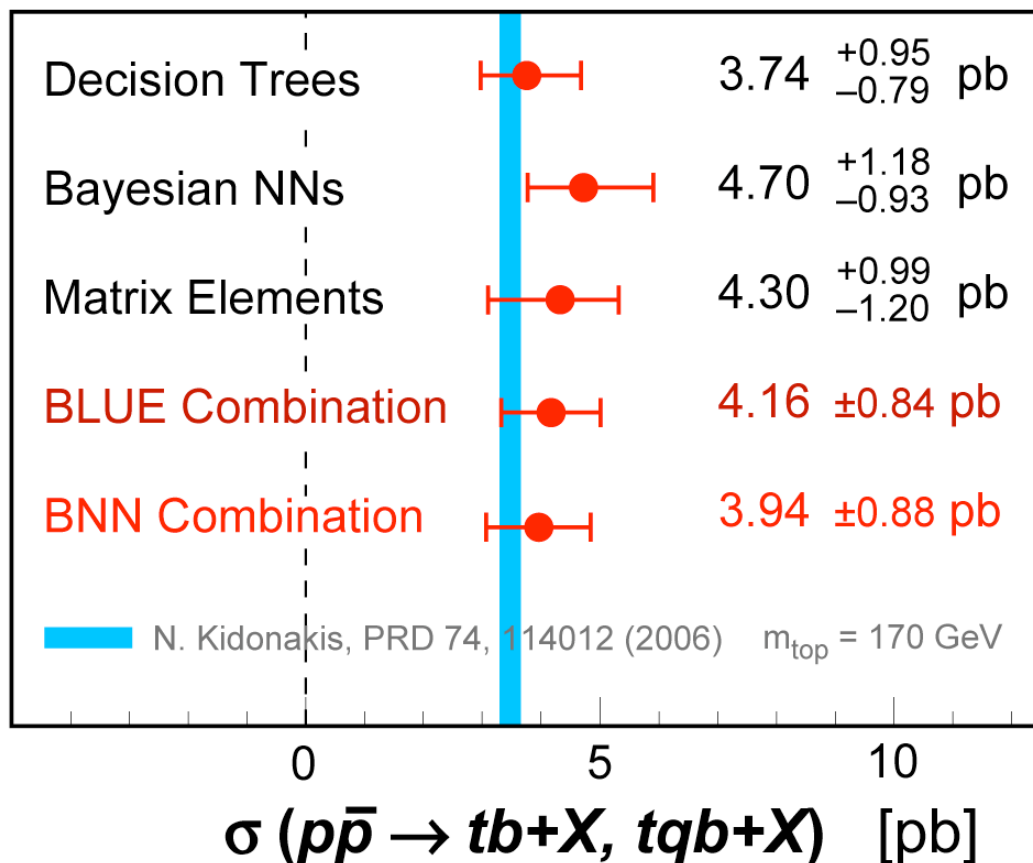
ET scale: 28 GeV



cross section summary

DØ 2.3 fb⁻¹

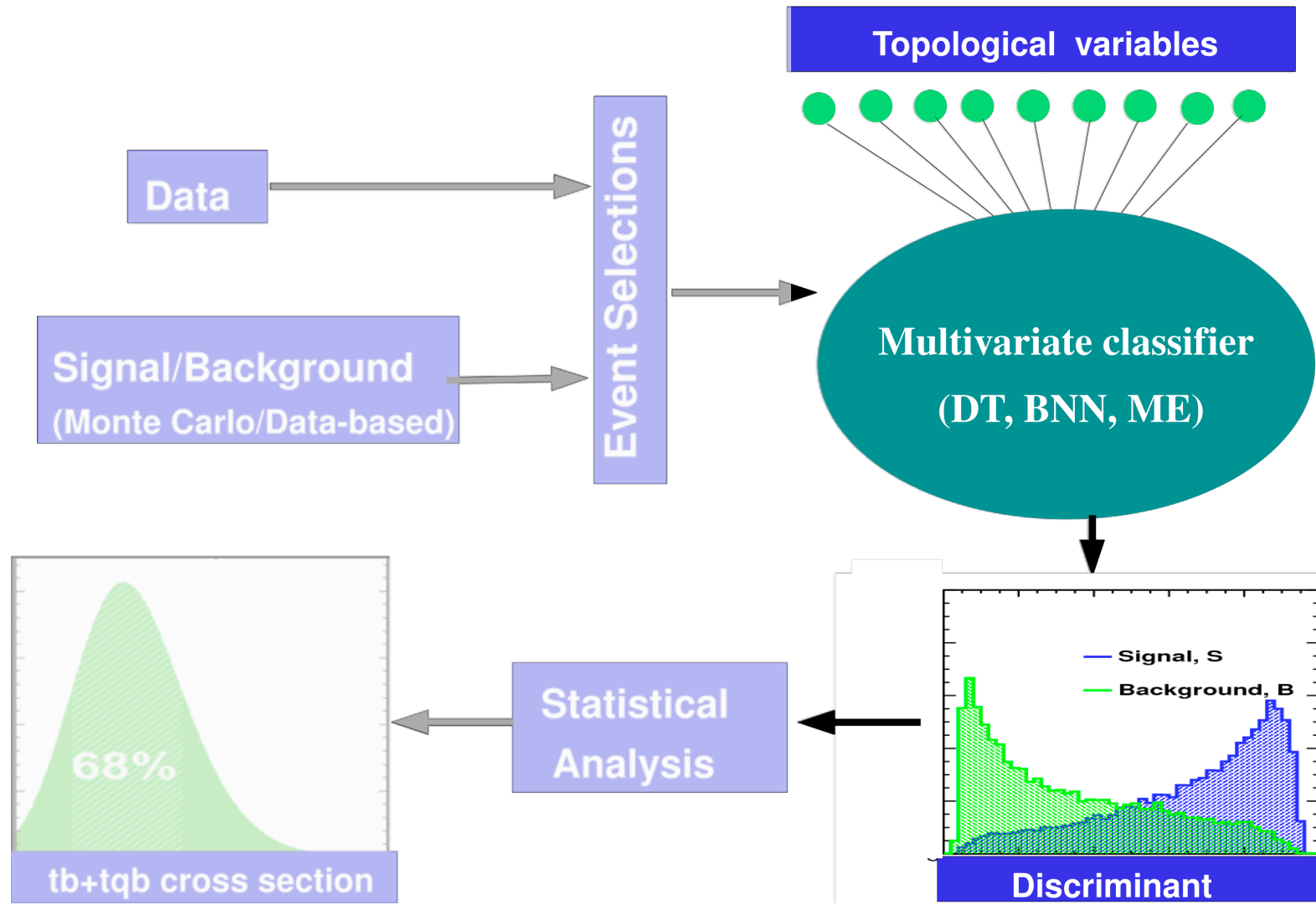
March 2009



Significance	
Expected	Measured
4.3 σ	4.6 σ
4.1 σ	5.2 σ
4.1 σ	4.9 σ
4.5 σ	5.0 σ



analysis flow chart



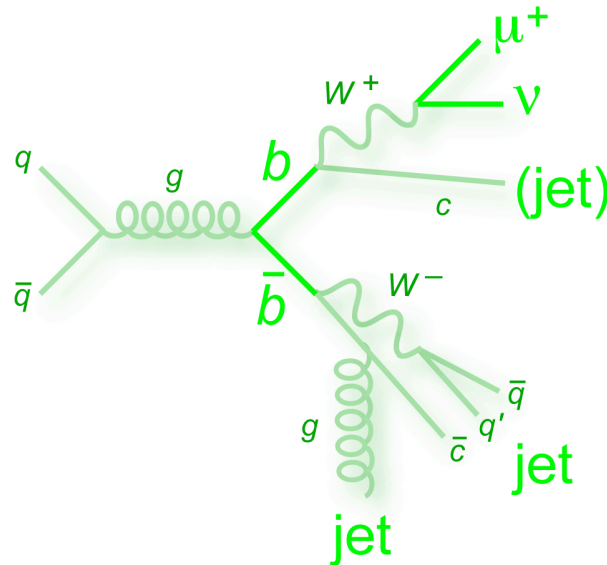
event counts – final selection:

- expected signal
- backgrounds
- observed

Event Yields in 2.3 fb⁻¹ of DØ Data	
e,μ, 2,3,4-jets, 1,2-tags combined	
<i>tb + tqb</i>	223 ± 30
<i>W</i> +jets	2,647 ± 241
<i>Z</i> +jets, dibosons	340 ± 61
<i>t</i> \bar{t} pairs	1,142 ± 168
Multijets	300 ± 52
Total prediction	4,652 ± 352
Data	4,519

modeling of backgrounds:

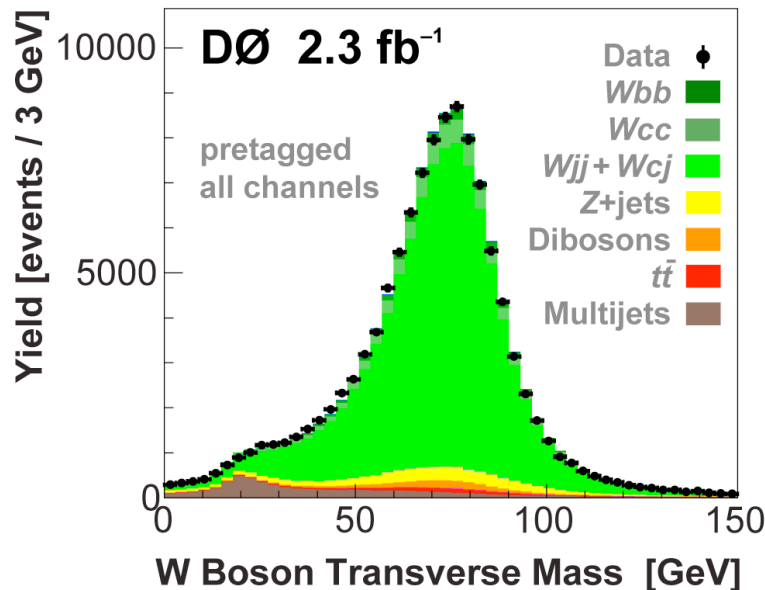
- W+jets:



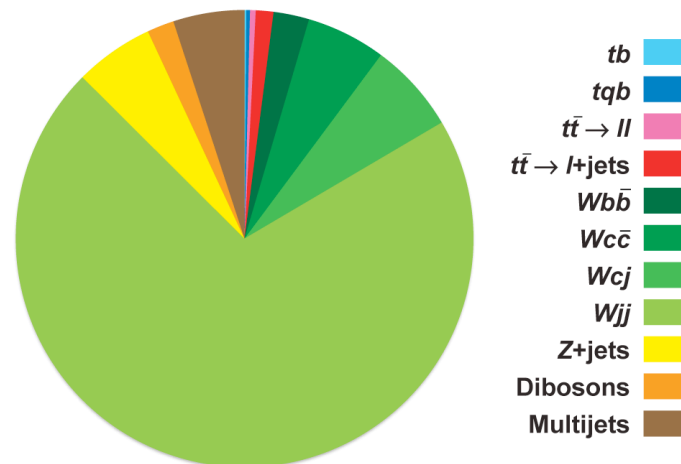
- modeled using ALPGEN
 - PYTHIA for parton hadronization
 - MLM parton-jet matching avoids double-counting final states
- $\eta(\text{jets})$, $\Delta\phi(\text{jet1}, \text{jet2})$, $\Delta\eta(\text{jet1}, \text{jet2})$ corrected to match data

1. bkg normalization pre b-tagging

- dominant background: W+jets



DØ Single Top 2.3 fb⁻¹ Signals and Backgrounds
(All channels combined, before *b*-tagging)



S:B =
1:259

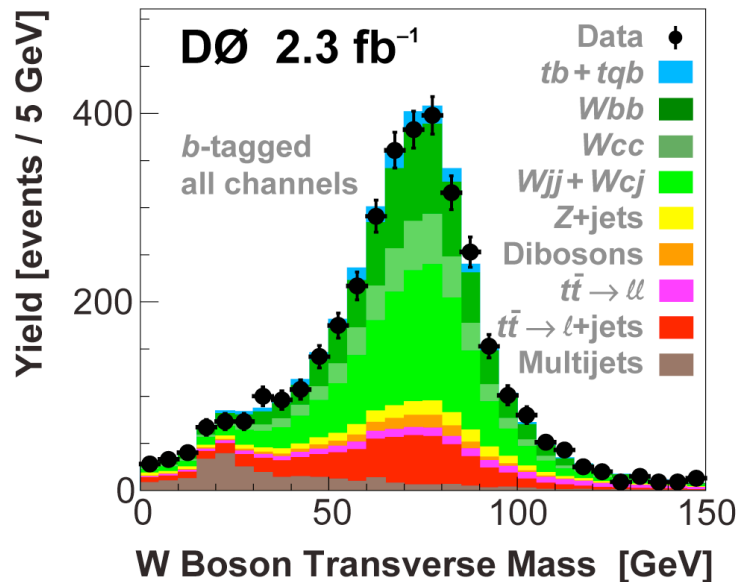
- Overall normalization for Wjets/mis-id determined by using iterative template fits to data using three sensitive variables: $p_T(l)$, $M_T(W)$ and missing E_T

$$N_{\text{pretag}}^{\text{data}} - N_{\text{bkgd}}^{\text{MC}} = S_{\text{W+jets}} N_{\text{W+jets}}^{\text{MC}} + S_{\text{multijet}} N_{\text{multijet}}^{\text{data}}$$

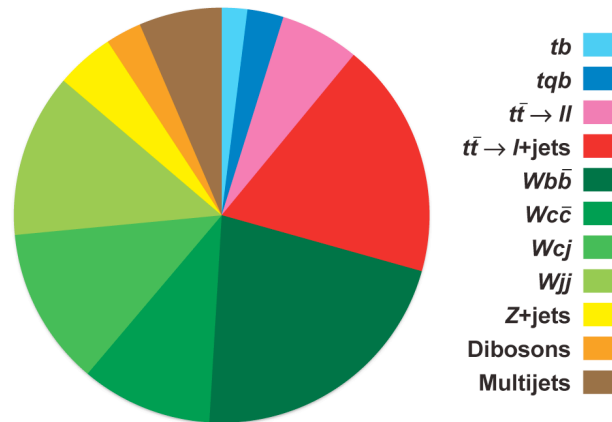
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2. bkg norm. post b-tagging

- W+HF (Wbb , Wcc , Wcj), top pair backgrounds are dominant



DØ Single Top 2.3 fb⁻¹ Signals and Backgrounds
(All channels combined, after *b*-tagging)

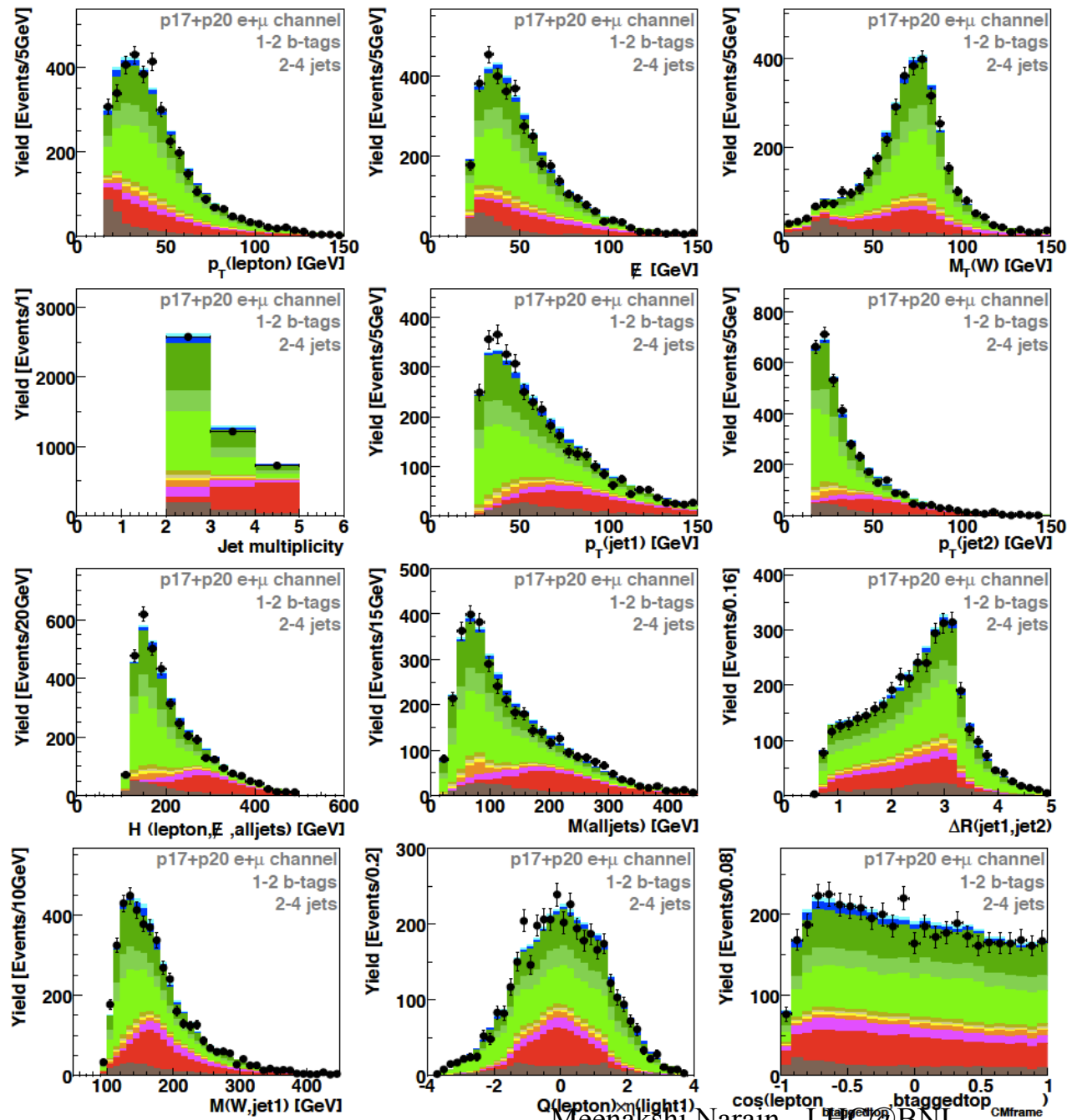


S:B

1:21 in 1Tag

1:15 in 2Tag

- W+heavy flavor correction factors
 - normalized to theory (use MCFM @ NLO)
 - 1.47 (Wbb , Wcc), 1.38 (Wcj)
 - additional empirical correction derived from two-jet data and simulation: includes zero-tag events
 - 0.95 ± 0.13 (Wbb , Wcc)

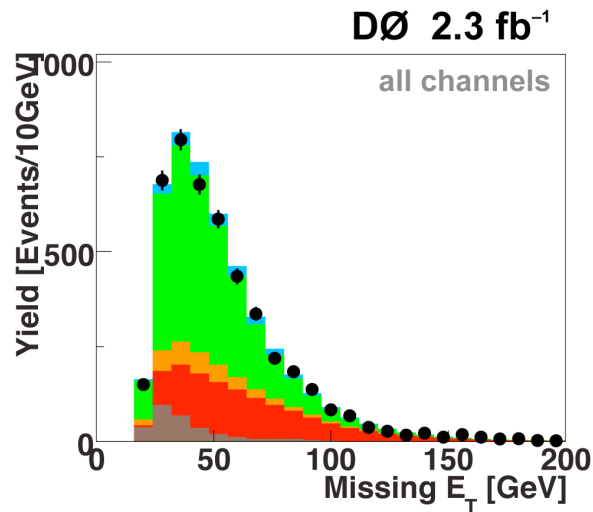


Data/MC
agreement (for
all channels
combined)

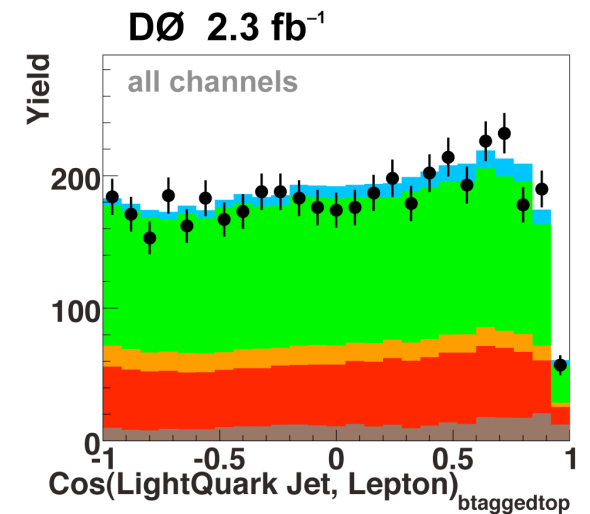
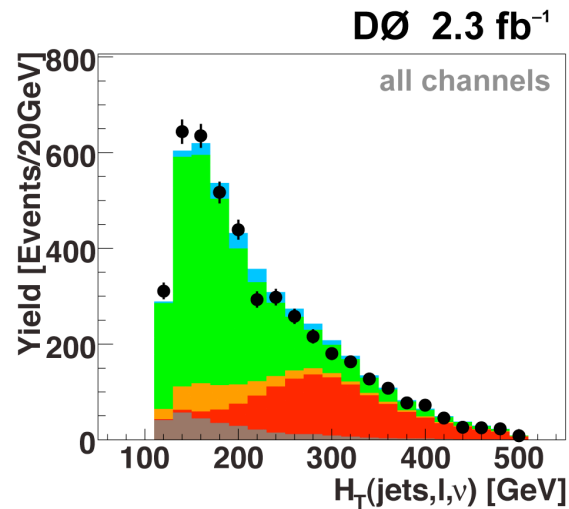


discriminating variable categories

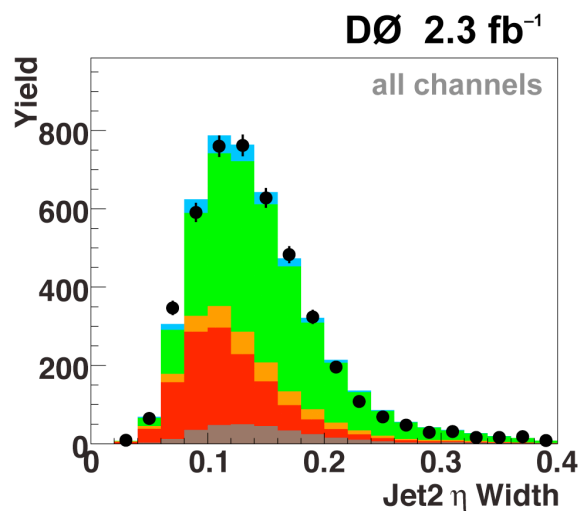
OBJECT KINEMATICS



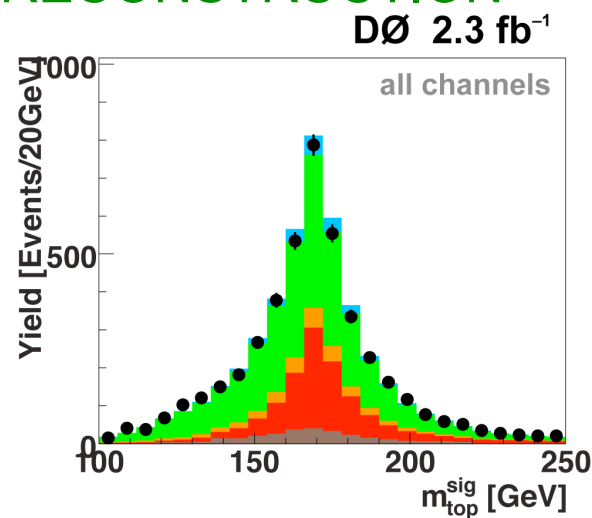
EVENT KINEMATICS



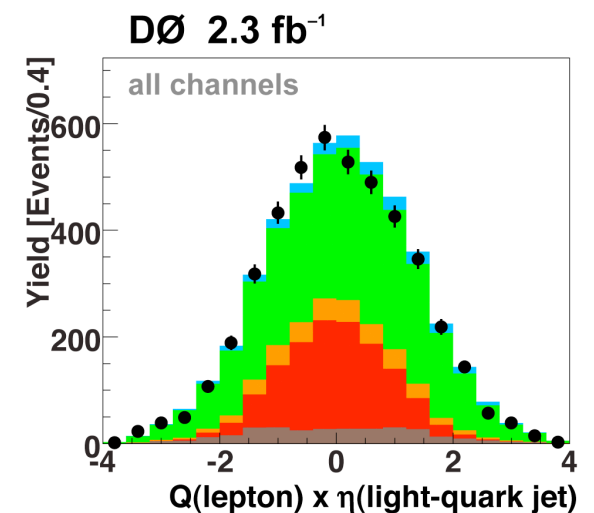
JET RECONSTRUCTION



TOP QUARK RECONSTRUCTION

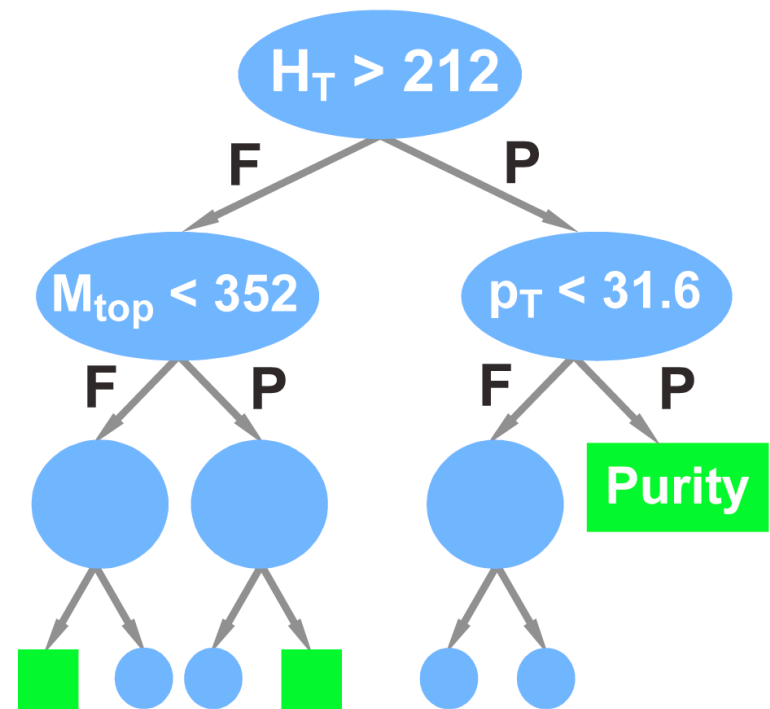


ANGULAR CORRELATIONS



boosted decision trees

- decision trees
 - idea: recover events that fail a cut
 - successively find cuts with best separation between signal and background
 - repeat recursively on each branch
 - stop when no further improvement or when too few events are left
 - terminal node is called a “leaf”
 - decision tree output = leaf purity



boosted decision trees

Best Variables to Separate Single Top from W+Jets

DØ 2.3 fb⁻¹ Analysis

Object kinematics	\cancel{E}_T
	$p_T(\text{jet2})$
	$p_T^{\text{rel}}(\text{jet1}, \text{tag-}\mu)$
	$E(\text{light1})$
Event kinematics	$M(\text{jet1}, \text{jet2})$
	$M_T(W)$
	$H_T(\text{lepton}, \cancel{E}_T, \text{jet1}, \text{jet2})$
	$H_T(\text{jet1}, \text{jet2})$
	$H_T(\text{lepton}, \cancel{E}_T)$
Jet reconstruction	$\text{Width}_\phi(\text{jet2})$
	$\text{Width}_\eta(\text{jet2})$
Top quark reconstruction	$M_{\text{top}}(W, \text{tag1})$
	$\Delta M_{\text{top}}^{\text{min}}$
	$M_{\text{top}}(W, \text{tag1}, S2)$
Angular correlations	$\cos(\text{light1}, \text{lepton})_{\text{btaggedtop}}$
	$\Delta\phi(\text{lepton}, \cancel{E}_T)$
	$Q(\text{lepton}) \times \eta(\text{light1})$

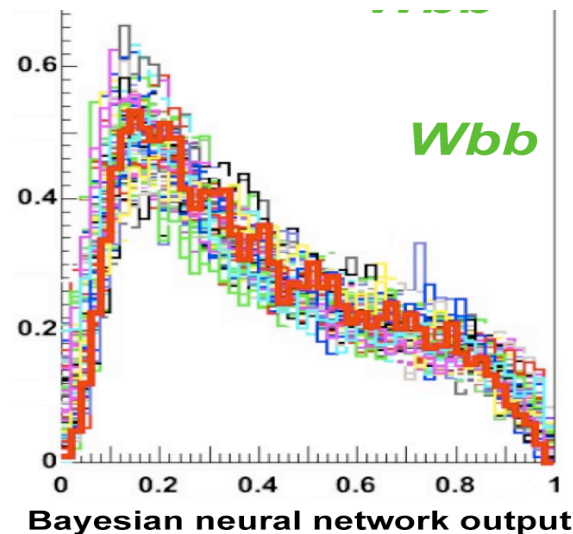
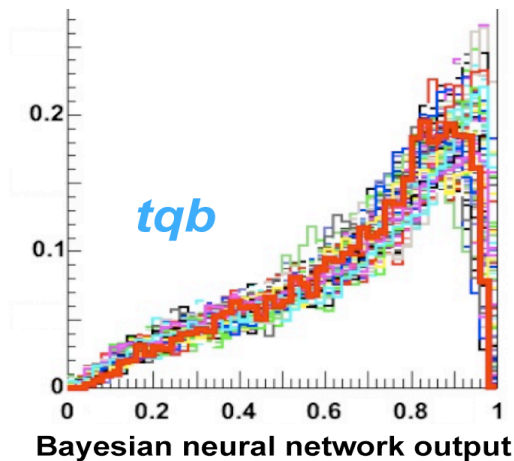
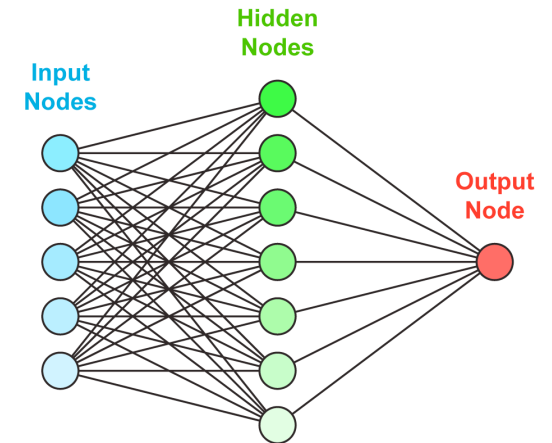
Best Variables to Separate Single Top from Top Pairs

DØ 2.3 fb⁻¹ Analysis

Object kinematics	$p_T(\text{notbest2})$
	$p_T(\text{jet4})$
	$p_T(\text{light2})$
Event kinematics	$M(\text{alljets}-\text{tag1})$
	$\text{Centrality}(\text{alljets})$
	$M(\text{alljets}-\text{best1})$
	$H_T(\text{alljets}-\text{tag1})$
	$H_T(\text{lepton}, \cancel{E}_T, \text{alljets})$
	$M(\text{alljets})$
Jet reconstruction	$\text{Width}_\eta(\text{jet4})$
	$\text{Width}_\phi(\text{jet4})$
	$\text{Width}_\phi(\text{jet2})$
Angular correlations	$\cos(\text{lepton}_{\text{btaggedtop}}, \text{btaggedtop}_{\text{CMframe}})$
	$Q(\text{lepton}) \times \eta(\text{light1})$
	$\Delta R(\text{jet1}, \text{jet2})$

bayesian neural networks

- Neural networks are nonlinear functions
 - defined by weights associated with each node
 - weights are determined by training on signal and background samples
- Bayesian neural networks improve on this technique
 - average over many networks weighted by the probability of each network given the training samples
 - Less prone to over-training
 - Network structure is less important – can use larger numbers of variables and hidden nodes



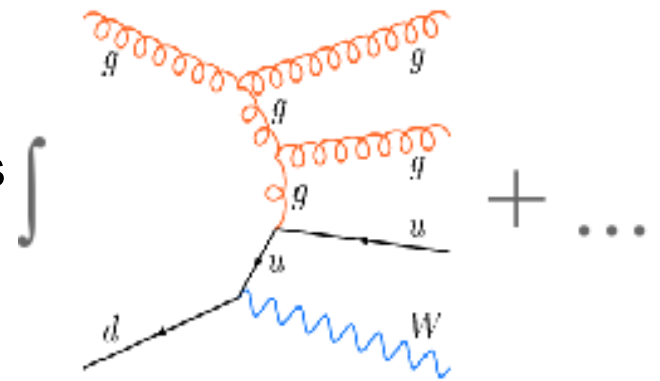
bayesian neural networks

- list of variables
 - example from one channel.

Rank	Variable
1	$M(\text{jet1}, \text{jet2})$
2	$M_T(W)$
3	$M_{top}(W, \text{tag1})$
4	ΔM_{top}^{min}
5	$H_T(\text{lepton}, \cancel{E}_T, \text{jet1}, \text{jet2})$
6	$M_{top}(W, \text{tag1}, S2)$
7	\cancel{E}_T
8	$Q(\text{lepton}) \times \eta(\text{light1})$
9	$\cos(\text{lepton}_{b\text{taggedtop}}, \text{btaggedtop}_{CM\text{frame}})$
10	$\cos(\text{tag1}, \text{lepton})_{b\text{taggedtop}}$
11	$p_T(\text{jet1})$
12	$\text{Width}_\eta(\text{jet2})$
13	$\Delta\phi(\text{lepton}, \cancel{E}_T)$
14	$\text{Width}_\phi(\text{jet2})$
15	$p_T(\text{jet2})$
16	$Q(\text{lepton}) \times \eta(\text{best1})$
17	$E(\text{jet2})$
18	$p_T(\text{best1})$
19	$p_T^{rel}(\text{jet1}, \mu)$
20	$\cos(\text{light1}, \text{lepton})_{b\text{taggedtop}}$
21	$\cos(\text{lepton}, Q(\text{lepton}) \times z)_{\text{besttop}}$

matrix elements

- method pioneered by DØ for top quark mass measurement
- use 4-vectors of reconstructed leptons and jets
- use matrix elements of main signal and background processes
- compute a discriminant



$$D_s(\vec{x}) = P(S|\vec{x}) = \frac{P_{Signal}(\vec{x})}{P_{Signal}(\vec{x}) + P_{Background}(\vec{x})}$$

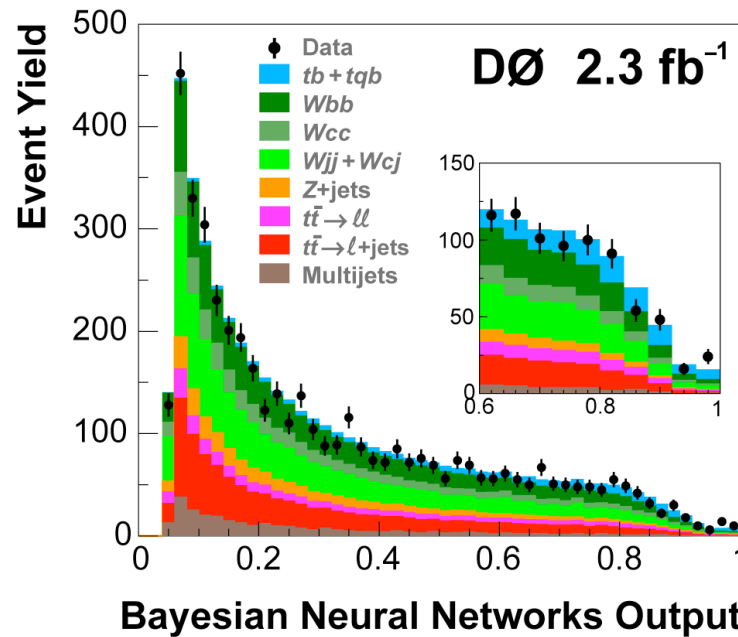
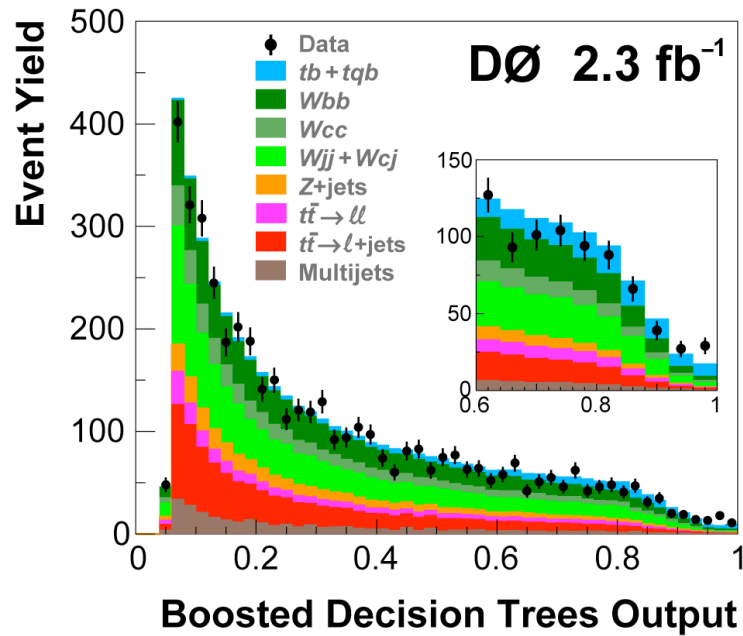
- define Γ_{signal} as a normalized differential cross section:

$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

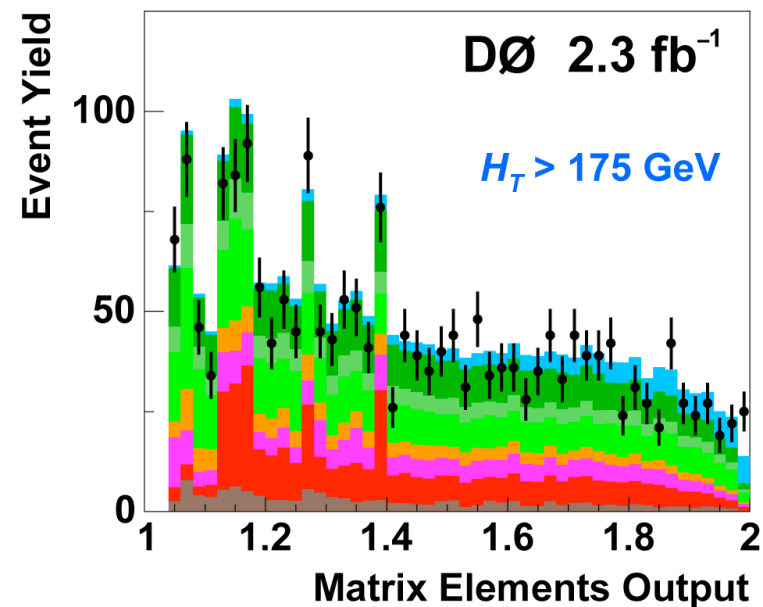
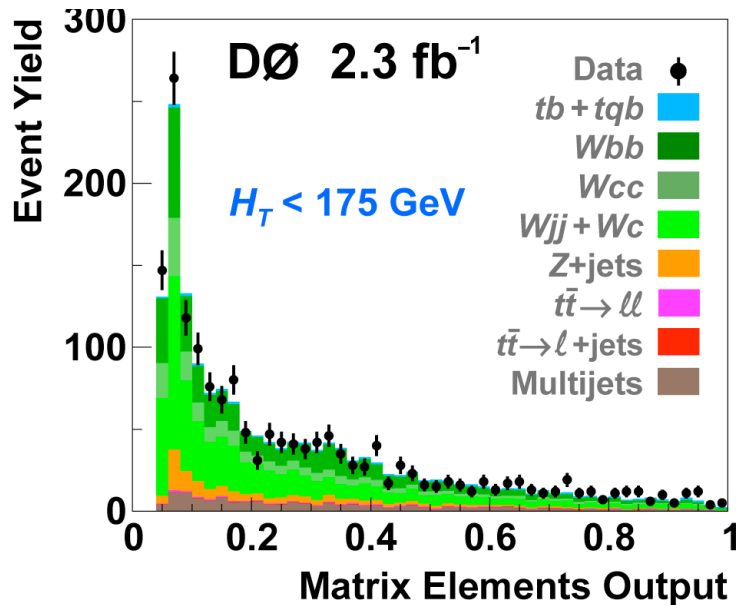
- 2-jets and 3-jets channels only

Matrix Elements used to Separate Single Top Signal from Background DØ 2.3 fb ⁻¹			
2 Jets		3 Jets	
$t\bar{b}$	$u\bar{d} \rightarrow t\bar{b}$	$t\bar{b}g$	$u\bar{d} \rightarrow t\bar{b}g$
tq	$ub \rightarrow td$ $d\bar{b} \rightarrow t\bar{u}$	tqg	$ub \rightarrow tdg$ $d\bar{b} \rightarrow t\bar{u}g$
		$tq\bar{b}$	$ug \rightarrow t\bar{d}\bar{b}$ $\bar{d}g \rightarrow t\bar{u}\bar{b}$
$Wb\bar{b}$	$u\bar{d} \rightarrow Wb\bar{b}$	$Wb\bar{b}g$	$u\bar{d} \rightarrow Wb\bar{b}g$
$W\bar{c}g$	$\bar{s}g \rightarrow W\bar{c}g$		
Wgg	$u\bar{d} \rightarrow Wgg$	$W\bar{u}gg$	$\bar{u}g \rightarrow W\bar{u}gg$
WW	$q\bar{q} \rightarrow WW$		
WZ	$q\bar{q} \rightarrow WZ$		
ggg	$gg \rightarrow ggg$		
$t\bar{t}$	$q\bar{q} \rightarrow t\bar{t} \rightarrow \ell^+ \nu b \ell^- \nu \bar{b}$		
$t\bar{t}$	$q\bar{q} \rightarrow t\bar{t} \rightarrow \ell^+ \nu b \bar{u} d \bar{b}$	$t\bar{t}$	$q\bar{q} \rightarrow t\bar{t} \rightarrow \ell^+ \nu b \bar{u} d \bar{b}$

final discriminant for the 3 methods

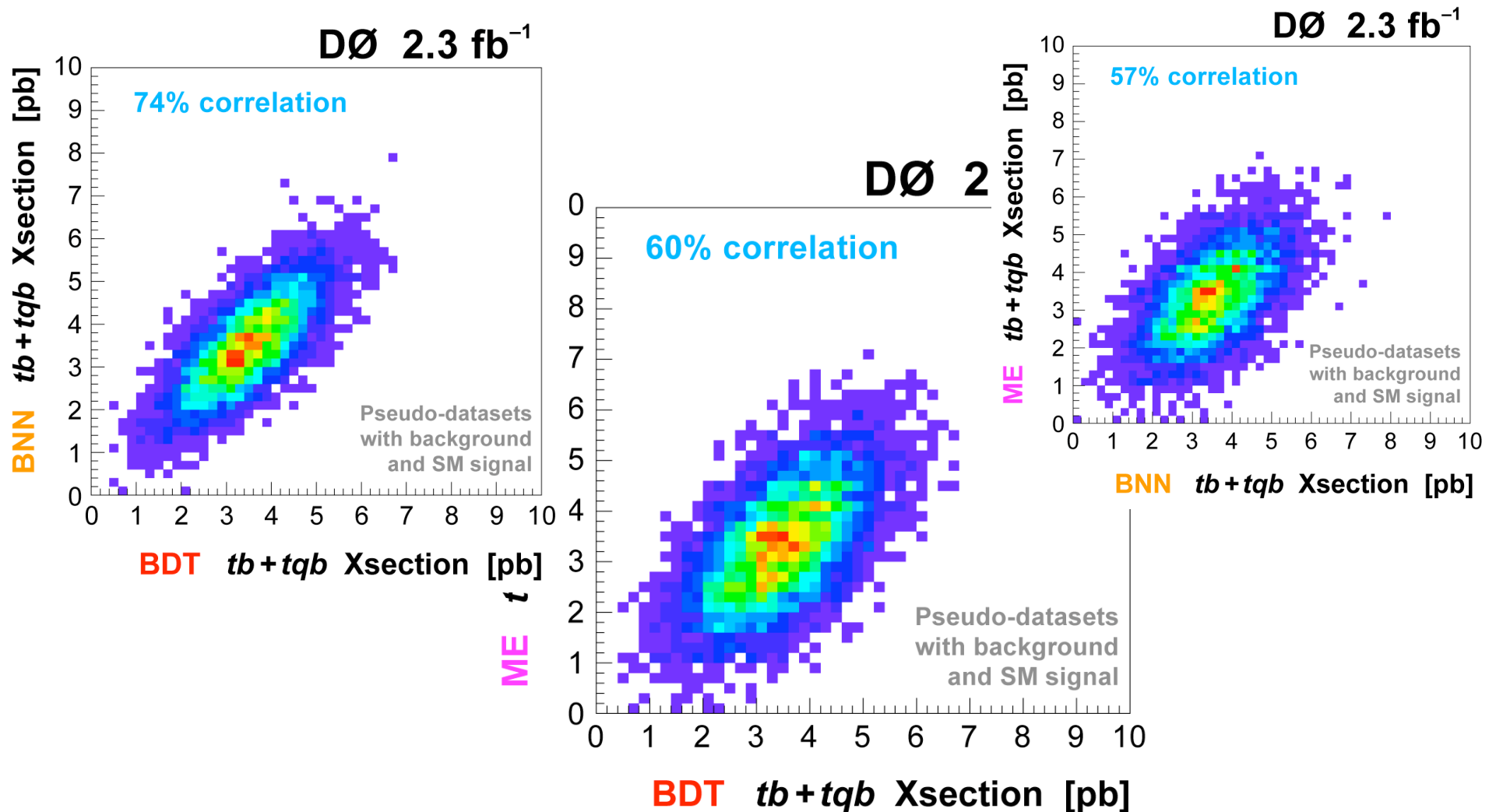


Signal
normalized to
measured x-sec



correlations between methods

- Even though all MVA analyses use the same data, they are not 100% correlated



Systematic uncertainties

Systematic Uncertainties

Ranked from Largest to Smallest Effect
on Single Top Cross Section

$D\emptyset$ 2.3 fb⁻¹

Larger terms

<i>b</i> -ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
<i>W</i> +jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
<i>b</i> -jet fragmentation	2.0%
<i>t</i> \bar{t} pairs theory cross section	12.7%
Lepton identification	2.5%
<i>Wbb</i> / <i>Wcc</i> correction ratio	5%
Primary vertex selection	1.4%

Systematic Uncertainties

Ranked from Largest to Smallest Effect
on Single Top Cross Section

$D\emptyset$ 2.3 fb⁻¹

Smaller terms

Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
<i>Z</i> +jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
<i>Z</i> +jets theory cross sections	5.8%
<i>W</i> +jets and multijets normalization to data	(1.8–3.9)% (<i>W</i> +jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen <i>W</i> +jets shape corrections	shape only
Trigger	5%

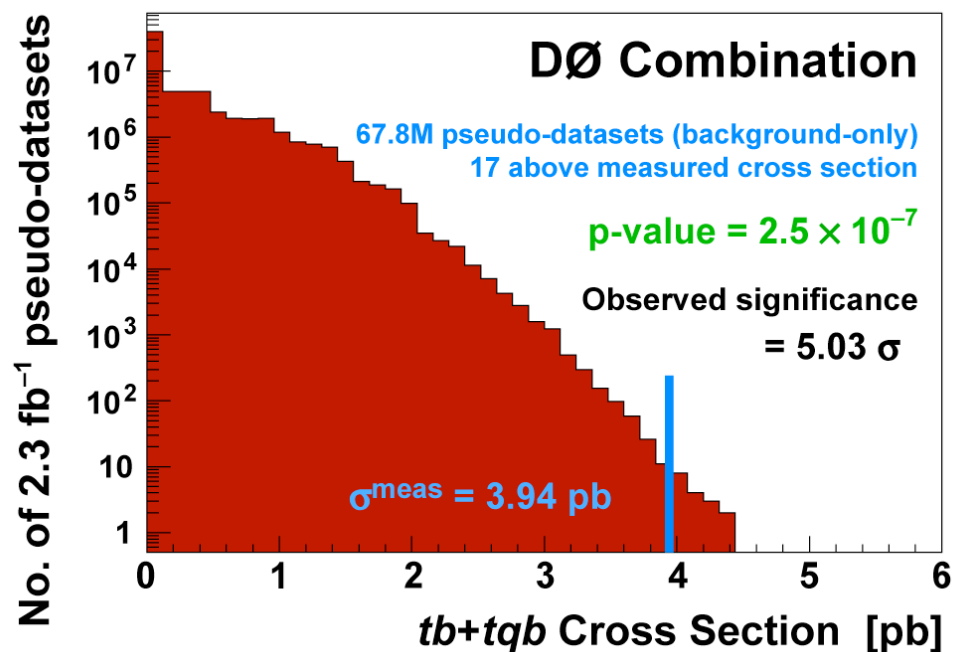
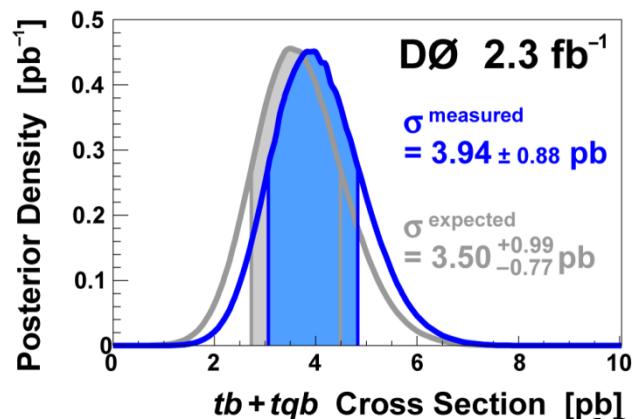
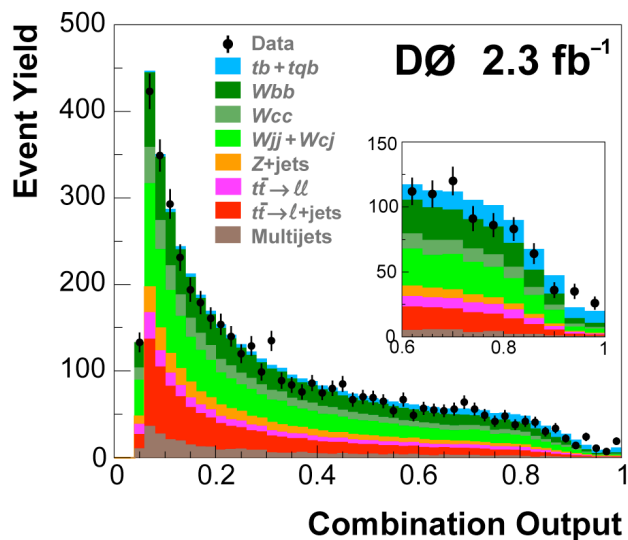


Combined results



$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

($m_t = 170 \text{ GeV}$)



$$p\text{-value} = 2.5 \times 10^{-7}$$

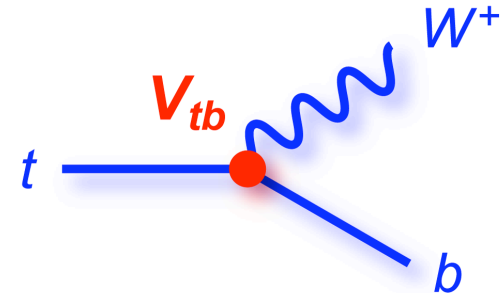
Measured Significance = 5.03σ

Lessons learned

- Lot of detailed work goes into making sure the data and MC agree.
- Control samples to verify distributions, estimate backgrounds, efficiencies for triggers, lepton-id etc.
- Validation of the inputs to the MVAs and output discriminants are well modeled.

CKM matrix element V_{tb}

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$



- Weak interaction eigenstates and mass eigenstates are not the same: there is mixing between quarks, described by CKM matrix
- general form of Wtb vertex:

$$\Gamma_{Wtb}^{\mu} = -\frac{g}{\sqrt{2}} \mathbf{V_{tb}} \left\{ \gamma^{\mu} [\mathbf{f_1^L} P_L + \mathbf{f_1^R} P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} [\mathbf{f_2^L} P_L + \mathbf{f_2^R} P_R] \right\}$$

- assume
 - sm top quark decay : $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
 - pure V-A : $f_1^R = 0$
 - CP conservation : $f_2^L = f_2^R = 0$
- do not assume
 - three quark families
 - CKM matrix unitarity
 - (unlike for measurements using $t\bar{t}$ decays)

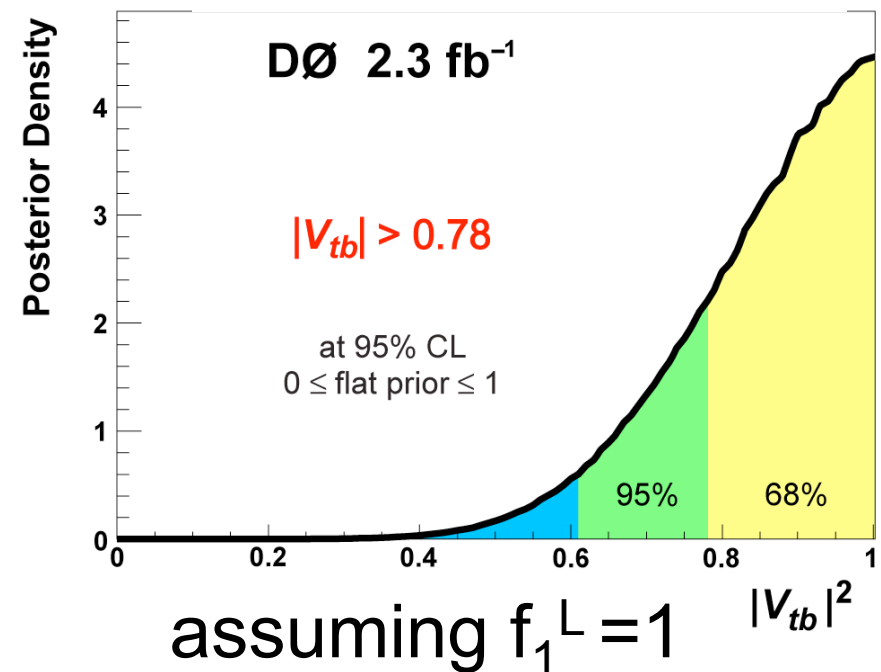
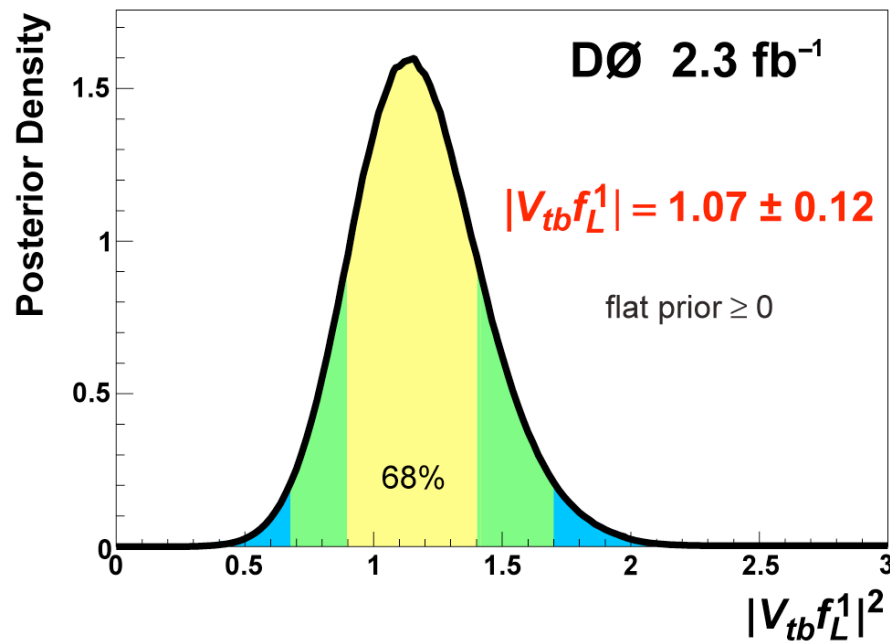
measurement of $|V_{tb}|$

- Use the measurement of the single top cross section to make a direct measurement of $|V_{tb}|$:

$$\sigma(tb, tqb) \propto |V_{tb} f_1^L|^2$$

- Calculate a posterior in $|V_{tb} f_1^L|^2$
- Measure the strength of the V–A coupling, which can be > 1

Additional Systematic Uncertainties for the $ V_{tb} $ Measurement	
DØ 2.3 fb ⁻¹	
For the $tb+qtb$ theory cross section	
Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling α_s	0.5%



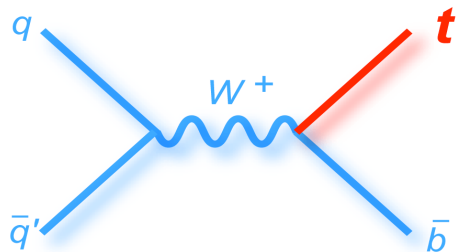
top quark coupling

- if top plays a special role in ewk symmetry breaking its couplings to W bosons may differ from predictions
- modifications to top quark interactions, in particular with weak gauge bosons, could yield the first signs of new physics
- most general CP-conserving W-t-b vertex involves four couplings

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.$$

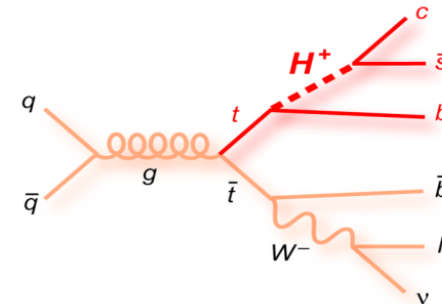
where, in the SM $f_1^L \approx 1$, $f_2^L = f_1^R = f_2^R = 0$

- probing tWb vertex:
Anomalous couplings in
single top quark production and decay



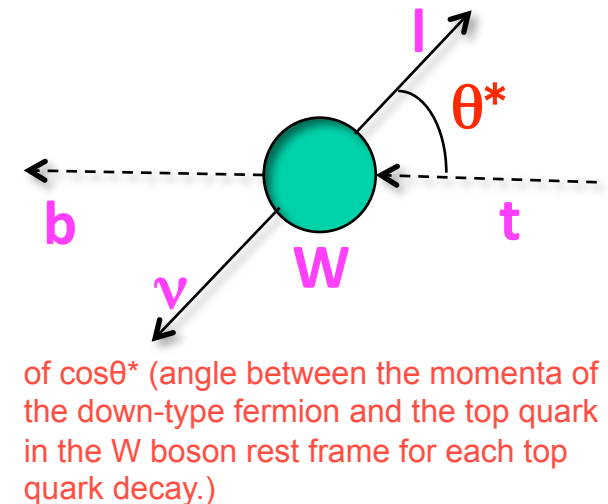
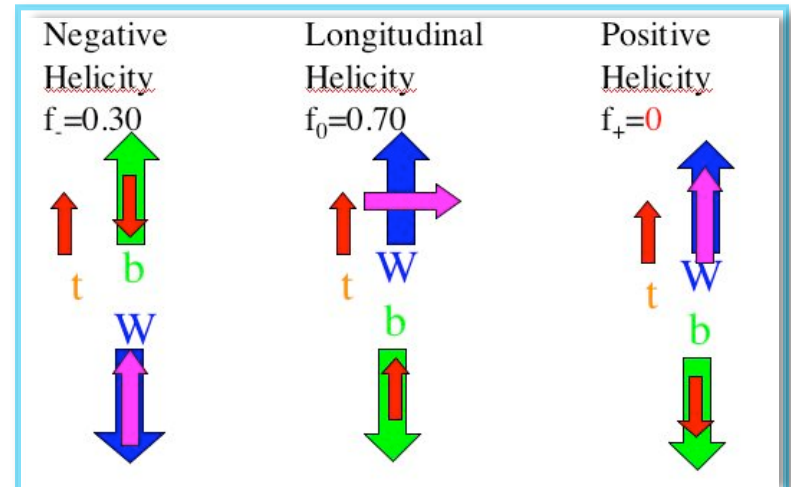
- Both measurements can be combined to fully specify the tbW vertex

W helicity In top pair decays



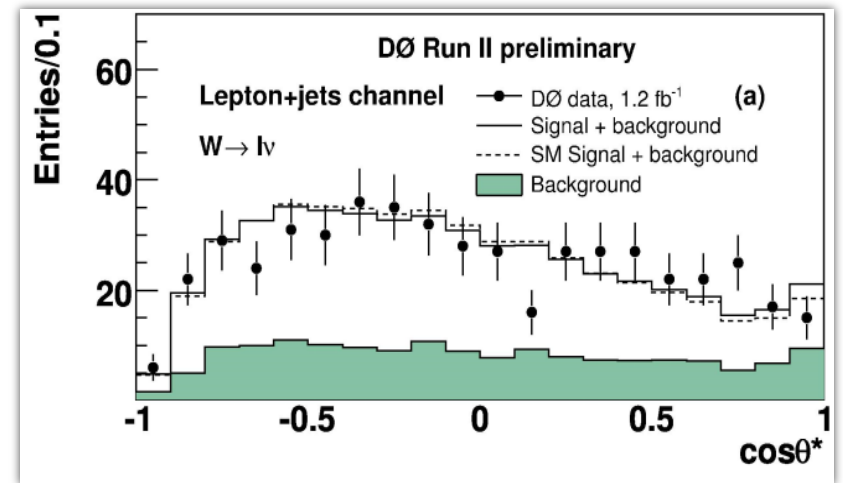
W boson helicity from $t \rightarrow Wb$ decays in top pair production

- sm predicts V-A coupling at Wtb
- \Rightarrow helicity of W boson
 $f_0 = 0.7, \quad f_- = 0.3, \quad f_+ = 0.0$
 (longitudinal, left-handed, right-handed)
- a different Lorentz structure of the $t \rightarrow Wb$ interaction would alter the fractions of W bosons produced in each polarization state.
- model-independent measurement based on reconstruction of $\cos\theta^*$ distribution - angle between lepton and top in W rest frame
- distribution of $\cos\theta^*$ depends on the W boson helicity fractions



top quark coupling

- Use a maximum likelihood fit, for the data to be consistent with the sum of signal and background in the $\cos\theta^*$ distribution
- The fit parameters are the W helicity fractions f_0 and f_+



- A model-independent measurement of the helicity of W bosons

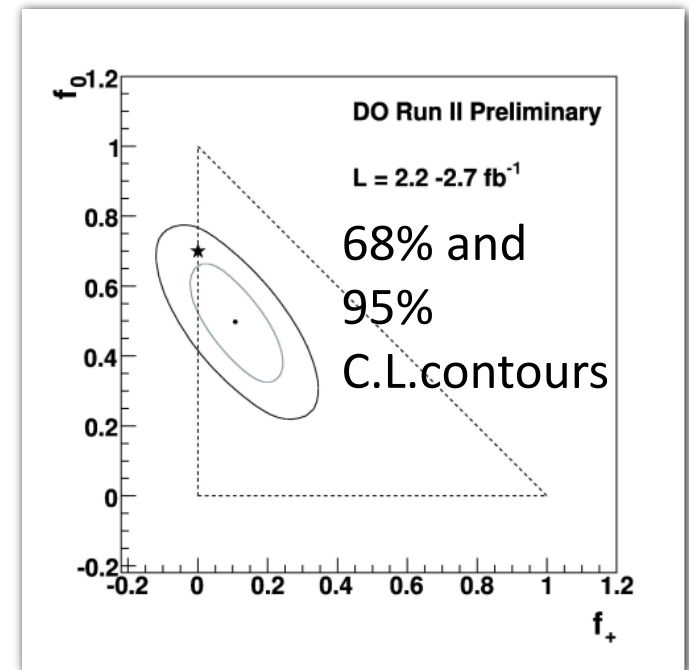
$$f_0 = 0.490 \pm 0.106 \text{ (stat.)} \pm 0.085 \text{ (syst.)}$$

$$f_+ = 0.110 \pm 0.059 \text{ (stat.)} \pm 0.052 \text{ (syst.)}$$

- if f_0 constrained to the standard model value

$$f_+ = 0.019 \pm 0.031 \text{ (stat.)} \pm 0.047 \text{ (syst.)}$$

- This is the most precise such measurement

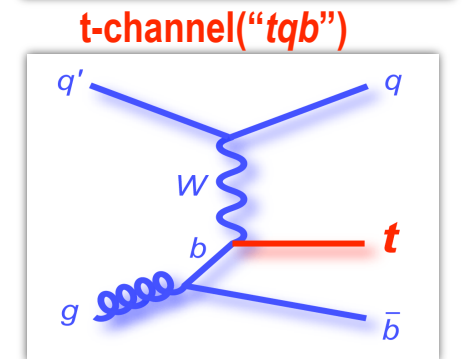
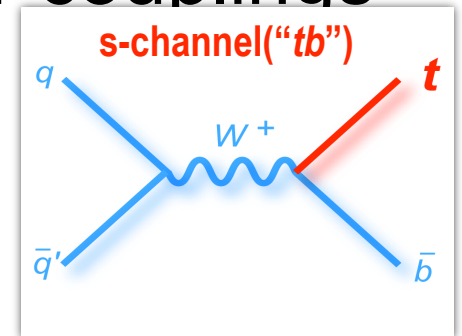


anomalous couplings in single top production

- Left & Right handed Vector and Tensor couplings

$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t$$

where, in the SM $f_1^L \approx 1$, $f_2^L = f_1^R = f_2^R = 0$ $+h.c.$

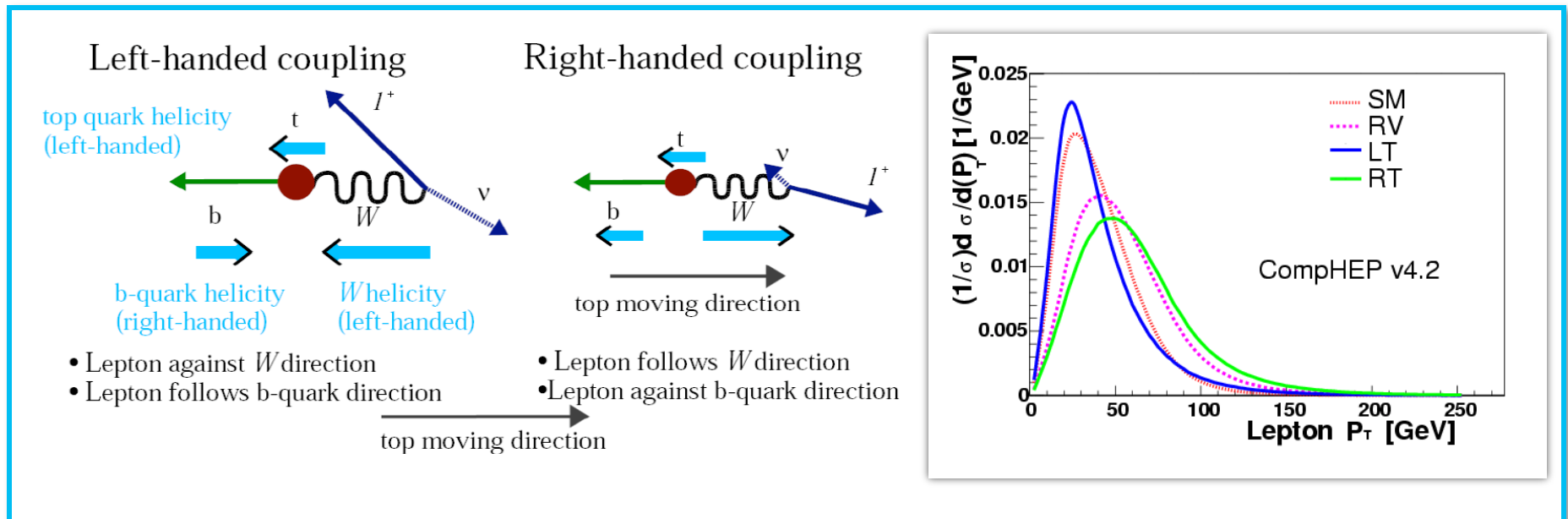


- Two non –zero couplings at a time
 - Consider 3 scenarios
 - Simultaneous limit on two couplings

Only f_1^L, f_1^R non-zero
 Only f_1^L, f_2^L non-zero
 Only f_1^L, f_2^R non-zero

anomalous couplings vs SM

- presence of anomalous couplings changes the production cross-section, and kinematics and angular distributions



multivariate analysis

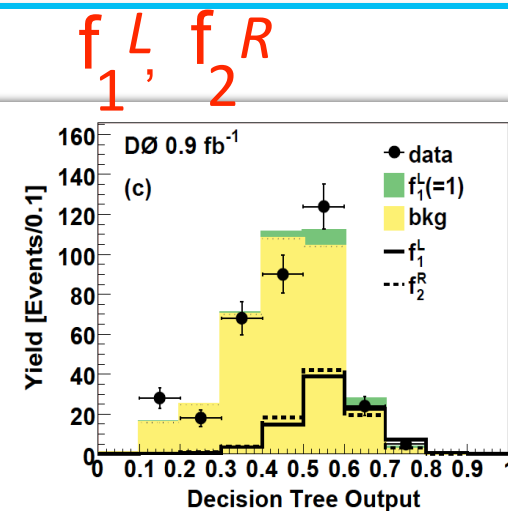
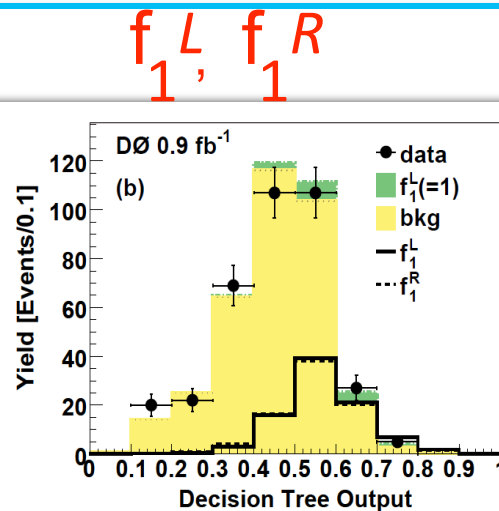
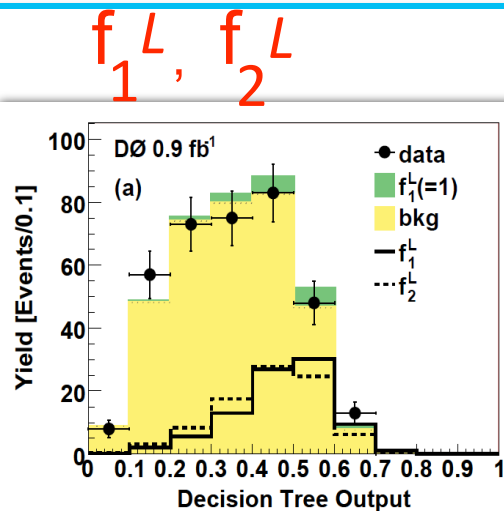
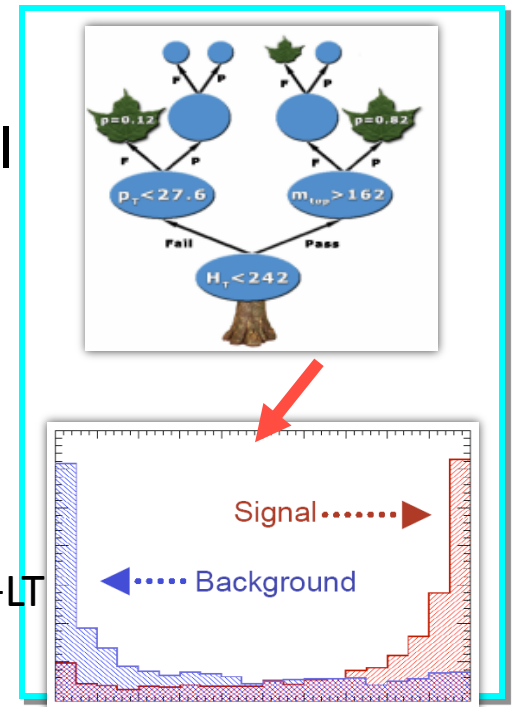
- Use Boosted Decision Trees to discriminate signal from background
- For every analysis, train 2 signals against sum of backgrounds

f_1^L, f_1^R scenario : (tb + tqb)LV + (tb + tqb)RV

f_1^L, f_2^L scenario : (tb + tqb)LV + (tb + tqb)LT + (tb + tqb)LV+LT

f_1^L, f_2^R scenario : (tb + tqb)LV + (tb + tqb)RT

$$\mathcal{L} = 1 \text{ fb}^{-1}$$



$$\mathcal{L} = 1 \text{ fb}^{-1}$$

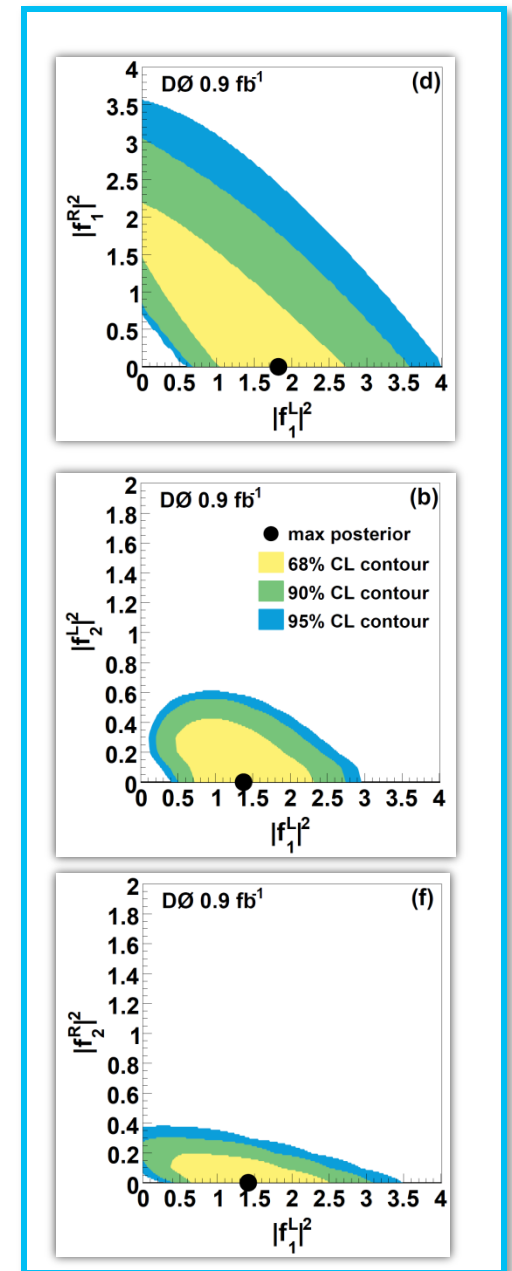
Limit Setting

- Bayesian approach for limit setting
- Simultaneous limit setting for two signals by calculating 2 dimensional posterior probability density

Scenario	Cross Section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5} \text{ pb}$	$ f_1^L ^2 = 1.4^{+0.6}_{-0.5}$ $ f_2^L ^2 < 0.5 \text{ at } 95\% \text{ C.L.}$
(L_1, R_1)	$5.2^{+2.6}_{-3.5} \text{ pb}$	$ f_1^L ^2 = 1.8^{+1.0}_{-1.3}$ $ f_1^R ^2 < 2.5 \text{ at } 95\% \text{ C.L.}$
(L_1, R_2)	$4.5^{+2.2}_{-2.2} \text{ pb}$	$ f_1^L ^2 = 1.4^{+0.9}_{-0.8}$ $ f_2^R ^2 < 0.3 \text{ at } 95\% \text{ C.L.}$

First experimental limits on tensor couplings!
(PRL 101, 221801 (2008))

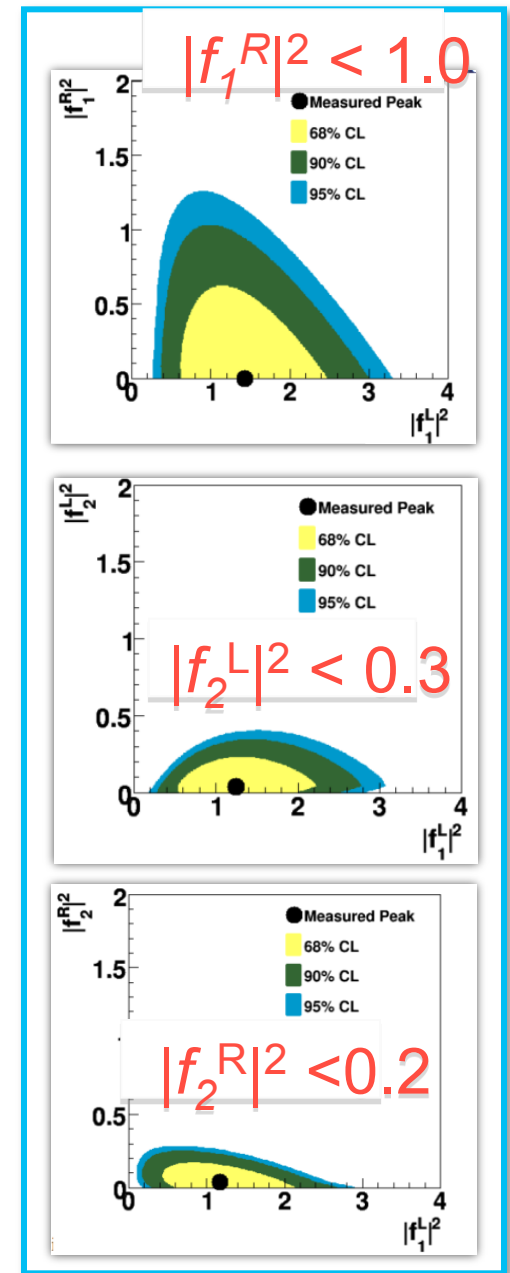
Meenakshi Narain - LHC@BNL



$$\mathcal{L} = 1 \text{ fb}^{-1}$$

Combination – tying it all together!

- W helicity measurement in top pair decays
- Anomalous couplings measurement in single top
- Bayesian analysis:
 - output of W helicity analysis forms input prior to single top anomalous couplings
- Observed posterior from data: single top and W helicity combined



analysis trends

- Looking at the whole picture
 - Tie together results in different channels and for different observables to compare the whole picture with predictions.
 - Mass vs cross section
 - Cross sections in different channels ($t \rightarrow Wb$ branching fraction, missing decay modes, charged Higgs, etc)
 - Wtb couplings (W helicity in $t\bar{t}$ decays and single top production/decay)

physics implications

- top quark is a known factor
 - Agrees with standard model (at least to precision probed at Tevatron – precision needed to estimate top as a background)
 - Can be simulated reliably with existing MC generators to estimate backgrounds to new physics
 - Provides important calibration point
 - b-tagging performance
 - jet energy scale
 - Tests of complex analysis chain of a know signal

physics opportunities

- top as a probe for new physics
 - New production modes
 - Top as a decay product
- measurements that are statistically limited at Tevatron
 - Rare top decays
 - Spin correlations
 - Single top production

conclusion

- top physics has come a long way since 1995
- top quark mass measured to 0.75%
 - reaching uncertainties below 1 GeV
- measurement of top properties and possible non-standard physics in t-W-b couplings are consistent with SM
- searches for new physics are continuing
- soon the torch will be passing to the LHC.

<http://www-d0.fnal.gov/Run2Physics/top/>

<http://www-cdf.fnal.gov/physics/new/top/top.html>

thank you

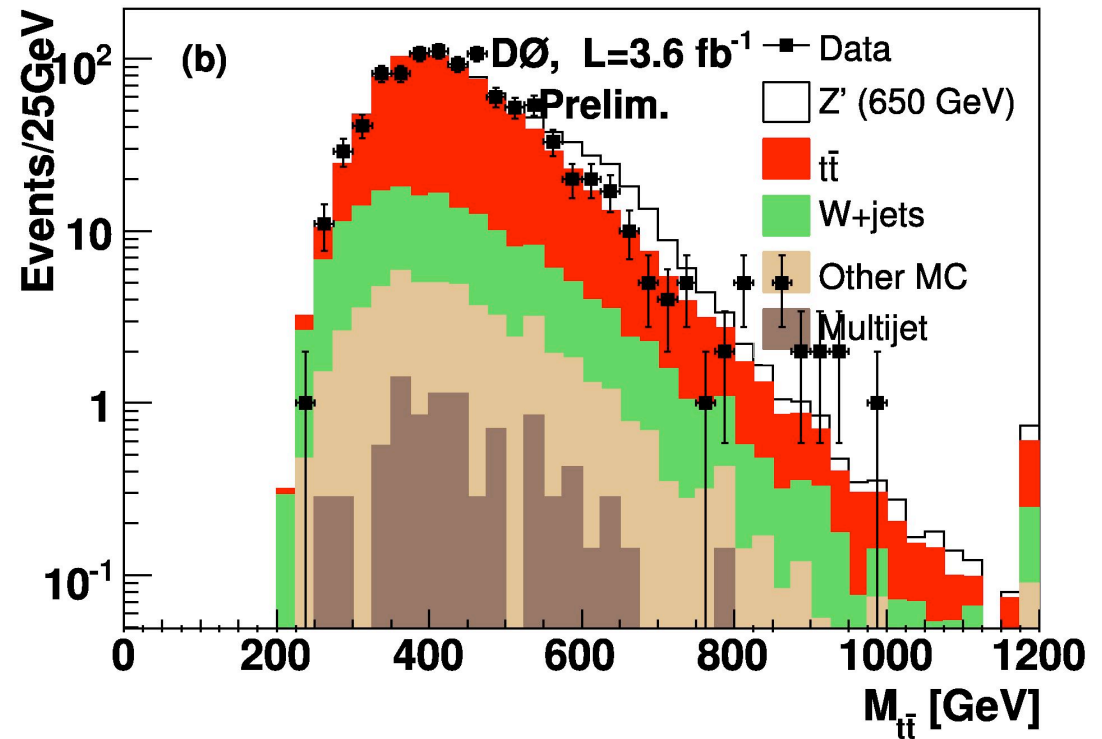


$t\bar{t}$ resonances

- D0 (3.6 fb^{-1})
 - technicolor $Z' \rightarrow t\bar{t}$

Hill & Parke, PRD 49 (1994) 4454

$M_{Z'} > 820 \text{ GeV}$
for $\Gamma_{Z'}/M_{Z'} = 1.2\%$



xsec syst

D0 l+jets b-tag

source	uncertainty
vertex	0.15 pb
e id	0.11 pb
μ id	0.08 pb
jet id	0.12 pb
non-W bkg	0.06 pb
jet response	0.30 pb
MC model	0.29 pb
b-tagging efficiency	0.48 pb
total	0.69 pb

kinematic likelihood

source	selection	fit	total
vertex	0.13 pb		0.13 pb
e id	0.10 pb		0.10 pb
μ id	0.06 pb		0.06 pb
jet id	0.10 pb	0.02 pb	0.12 pb
non-W bkg	0.10 pb		0.10 pb
jet response	0.35 pb	0.26 pb	0.11 pb
MC model	0.13 pb	0.09 pb	0.11 pb
template stats		0.15 pb	0.15 pb
total			0.36 pb

searches for non-standard physics

- quarks with charge $4/3e \rightarrow$ disfavored
- FB $t\bar{t}$ asymmetry \rightarrow consistent with sm
- 4th generation t' quarks $\rightarrow m > 284$ GeV
- scalar top production \rightarrow no evidence
- charged Higgs bosons \rightarrow limits on H^\pm
- $t\bar{b}$ resonances $\rightarrow t\bar{b}, t \rightarrow H^\pm b$
- $t\bar{t}$ resonances
- FCNC decays of top quarks